GLAS Altimeter Post-Launch Calibration/Validation Plan

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DOCUMENT REVISIONS

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1.0 INTRODUCTION

The post-launch Calibration/Validation (CV) plans for the Geoscience Laser Altimeter System (GLAS) are summarized in this document. For purposes of this document, the following definitions have been used:

- Verify: to establish the truth, accuracy or reality of[1]
- Calibrate: to standardize (as a measuring instrument) by determining the deviation from a standard so as to ascertain the proper correction factors[1]
- Validate: to make valid, substantiate, confirm; to give official sanction, confirmation or approval to[2]

In a broad sense, CV plans for GLAS will verify the measurements and the performance of the instruments. The process of verification may lead to new calibration corrections. Hence, the terms Verification and Calibration primarily refer to Level 1 products, while Validation refers to Level 2 and higher data products. The Level 2 products are generated from the Level 1 products plus ancillary data not generated directly by the GLAS instrument. There is an inevitable link between these definitions and the processes used to perform verification, calibration and validation. As a consequence, all three activities are integrated together in this plan.

The fundamental objective is to validate the science data products to ensure, within time and budget constraints, that appropriate geophysical interpretations can be drawn from the data products. The identification and removal of nongeophysical artifacts from the data is an important element of the CV process. If such artifacts cannot be removed, a level of geophysical uncertainty that can be attached to the data products must be established. An important additional aspect is to ensure that the GLAS measurements are fully characterized and understood to enable their comparison with similar data that will be collected on future missions. This latter objective is especially important since it cannot be assured that a followon mission will overlap with this first mission.

With the previously stated objectives as background, this plan addresses the calibration/validation of the GLAS altimeter mode. A separate plan has been prepared for the atmospheric channel (Palm, et al., 2000); however, some overlapping aspects are treated in this plan for altimetry. Both plans will be updated, revised and extended as appropriate. In general, final prelaunch versions will be issued in the few months prior to launch and the plan will be revisited early in the post-launch period, as well as throughout the mission.

1.1 Measurement and Science Objectives

GLAS is a laser altimeter designed to measure ice-sheet topography and associated temporal changes, as well as cloud and atmospheric properties. In addition, operation of GLAS over land and water will provide along-track topography.

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1. Merriam-Webster’s Collegiate Dictionary, 1997
2. Random House Webster’s Unabridged Electronic Dictionary, 1996

The GLAS science requirements (GLAS Science Team, 1997) address the specific requirements for the instrument. In summary:

• Cryosphere: the measurements should support determination of elevation change to an accuracy of 1.5 cm/yr in a 100 km x 100 km region where surface slopes are < 0.6° (1:100), which is typical for more than 80% of the polar ice-sheet surface; however, on the East Antarctic plains where surface slopes are < 0.2°, the accuracy requirement is 0.5 cm/yr in a 200,000 km^2.

• Land: the measurements should support determination of land elevation with an accuracy of better than 10 m and a spatial accuracy of 100 m or better at point locations on a global basis.

• Atmosphere: determine cloud top heights with a vertical accuracy of 75 m, thin cloud and aerosol optical depth with an accuracy of 30%, planetary boundary layer height with an accuracy of 150 m and lifting condensation layer to 200 m accuracy.

The cryosphere and land requirements will be met using a laser altimeter, which measures the distance from a reference point within the altimeter to the Earth's surface. The cryosphere requirement is by far the most stringent, and requires full knowledge of all instrument biases and their temporal change. Determination of such biases represents a prime objective of this Calibration/Validation Plan. With knowledge of the altimeter instrument position with respect to the Earth center of mass and knowledge of the direction of the laser beam at transmission, including instrumental biases, the illuminated spot on the surface of the Earth can be determined with respect to the Earth center of mass. Analysis of these spot positions within specified regions provides an inferred measurement of surface change.

The GLAS altitude measurement, referred to as the *altimeter-mode*, is based on the time interval between the transmission of a 1064 nm laser pulse and receipt of its surface echo. The determination of the position of the instrument in space is obtained with an on-board Global Positioning System (GPS) receiver and ground-based laser ranging, a process referred to as precision orbit determination. Two GPS receivers are carried for redundancy. The GLAS laser pointing direction is determined from a system of CCD cameras that image the outgoing laser pulse against the star field as well as a system of gyros, a process referred to as precision attitude determination (PAD).

The GLAS atmospheric lidar measurements use the 1064 nm laser pulse and a 532 nm pulse. The green pulse is to measure backscatter, thereby enabling determination of planetary boundary layer height and aerosol optical depth, for example.

The methodology planned to be used for the generation of the data products is described in a series of Algorithm Theoretical Basis Documents (ATBD). These documents were peer reviewed in April 1999 and subsequently modified. The documents are:

• Rim and Schutz (2000) describing the POD process
• Bae and Schutz (2000), describing the PAD process
• Zwally, et al. (2000), describing the range and surface characterization from the laser pulse waveform
• Schutz (2000), describing the geolocation
• Herring and Quinn (2000), describing the troposphere delay correction for the altimetry channel
• Yi, et al.(2000), describing the tide correction
• Palm, et al.(2000), describing the atmospheric channel

1.2 Instrument and Spacecraft Description

The ICESat Observatory, which consists of the spacecraft bus and the GLAS instrument, is illustrated in Fig. 1.2.1a (zenith side view) and Fig. 1.2.1b (nadir side view). The elements of the observatory that are relevant to the generation of the science products are:

GLAS altimeter/lidar - The instrument has been developed and built at NASA Goddard. The altimeter mode is based on the time of flight concept common to all altimeters. The measurement is based on the round trip travel time of a laser pulse transmitted by the instrument and echoed by the surface (ice, land, ocean, clouds). The lidar mode measures backscatter of the laser pulse to determine atmospheric properties.

Stellar Reference System (SRS) - The SRS is a subsystem in GLAS which measures the pointing of the laser beam with respect to the star field. The SRS consists of several components: a star tracker (Instrument Star Tracker, IST), a laser reference camera (LRC) and a laser profiling array (LPA). The SRS is mounted on the GLAS optical bench with the lasers. The IST provides information about the orientation of the optical bench with respect to the stars and the LRC/LPA provide information about the direction of the transmitted laser pulse with respect to the optical bench.

Hemispherical Resonator Gyro (HRG) - The HRG provides additional information to support the determination of the optical bench orientation in space. The HRG measures changes in orientation, or angular rates. The SRS and the HRG support the determination of the spatial orientation of the optical bench on which the GLAS instrumentation is mounted, referred to here as *precision attitude determination (PAD)*.

Spacecraft Bus - The ICESat spacecraft bus is a derivative of the RS-2000 commercial design from Ball Aerospace Systems Group, Boulder CO. The spacecraft provides power to GLAS and handles all communications with the ground stations, including transmittal of GLAS science data. The communications include commands for the instrument and spacecraft bus, as well as the transmittal of science data from the instrument. The bus contains the propulsion module that is required for orbit maintenance. The bus includes two star trackers mounted on the zenith side of the bus, which are required for attitude control of the observatory. Attitude control is accomplished with momentum wheels and magnetic torquers.

Global Positioning System Receiver (GPSR) - Two high precision GPS receivers with antennas are mounted on the observatory. The GPSR supports the determination of high accuracy ICESat Observatory positions, known as *precision orbit determination (POD)*. The receiver provides measurements using the two GPS L-band frequencies for removal of the ionosphere. Only one receiver operates at a time. The GPS antennas are located on the zenith side of the spacecraft bus.

Laser reflector array (LRA) - The LRA has two purposes: 1) support calibration/validation of the POD using the GPSR and 2) provide a passive backup system for POD. The LRA enables high accuracy laser ranging measurements to be made by ground-based satellite laser ranging (SLR) stations. The LRA is mounted on the nadir side of the bus.

Fig. 1.2.1a ICESat observatory illustrated in orbit. GLAS is shown in the upper right with the one meter telescope on the Earth-side (nadir) and the thermal radiator panels on the right and left sides of GLAS; the stellar reference system is shown on the zenith-side. The solar panels are depicted on the right and left sides of the spacecraft bus; the concentric rings on the zenith-side of the bus are the GPS antennas and the two bus star trackers are shown near the GLAS attachment region. (Figure provided by Ball Aerospace Systems Division)

Fig. 1.2.1b Nadir side of ICESat observatory illustrated in orbit. In this view, the array used for ground-based laser ranging is shown on the third stalk from the left on the nadir side, near the GLAS telescope.

1.2.1 Geoscience Laser Altimeter System (GLAS)

The GLAS instrument, developed and built at NASA Goddard, is illustrated in Fig. 1.2.2. The instrument contains several components mounted on a rigid optical bench. There are three lasers to meet the requirement for a three year lifetime with a five year goal. Only one laser operates at any time. The optical path for the transmitted laser pulse has a single transmission point from the optical bench to the ground, which requires the use of flip mirrors to insert the laser pulse from the respective laser units into the optical path. In the altimeter-mode, the laser pulse echoed from the surface illuminates a detector and the analog output is digitized with a 1 GHz sampler. The altimeter-mode contains two detectors and two digitizers for redundancy. The detector and digitizer combination can be independently selected. Each digitizer has an independent 2 GHz oscillator and the active oscillator also provides timing information. In addition to digitizing the return pulse, the transmitted laser pulse is digitized and both pulses are transmitted to the ground for analysis. A primary application of the digitized pulses is the determination of the pulse travel time interval, which provides the altitude. In addition, analysis of the return pulse provides characterization of the surface, such as a measure of roughness. The altimeter channel operates at 1064 nm and produces a 70 meter illuminated spot on the surface.

The instrument is designed for operation in both day and night conditions. To maintain thermal stability, GLAS will operate continuously; hence, data will be acquired over ice, land and water surfaces, as well as a variety of atmospheric conditions.

The lidar-mode of the instrument contains eight SPCM detectors. In normal flight operation, all eight detectors will operate; however, individual detectors can be deactivated. The atmospheric channel uses a 532 nm pulse.

1.2.2 Stellar Reference System (SRS)

The IST (Raytheon Optical Systems, Inc., ROSI HD-1003) provides a star image with an 8° field of view at a 10 Hz rate. The star images are used to determine the orientation of the optical bench in space. The LRC samples the laser beam at 10 Hz, as well as a 0.5° field of view star field that overlaps the IST star field. The overlapping star fields provide information for verification of alignment between the instruments. By imaging the outgoing laser beam in the LRC, the direction of the laser beam with respect to the star field is measured. In addition, the LPA samples the outgoing laser pulse at 40 Hz (each laser shot) to enable assessment of the laser stability.

1.2.3 Hemispherical Resonator Gyro (HRG)

The hemispherical resonator gyro (built by Litton) augments the IST by providing attitude rate information. The IST and the HRG data will be used for the determination of the spatial orientation of the optical bench, a process referred to as *precision attitude determination (PAD)*.

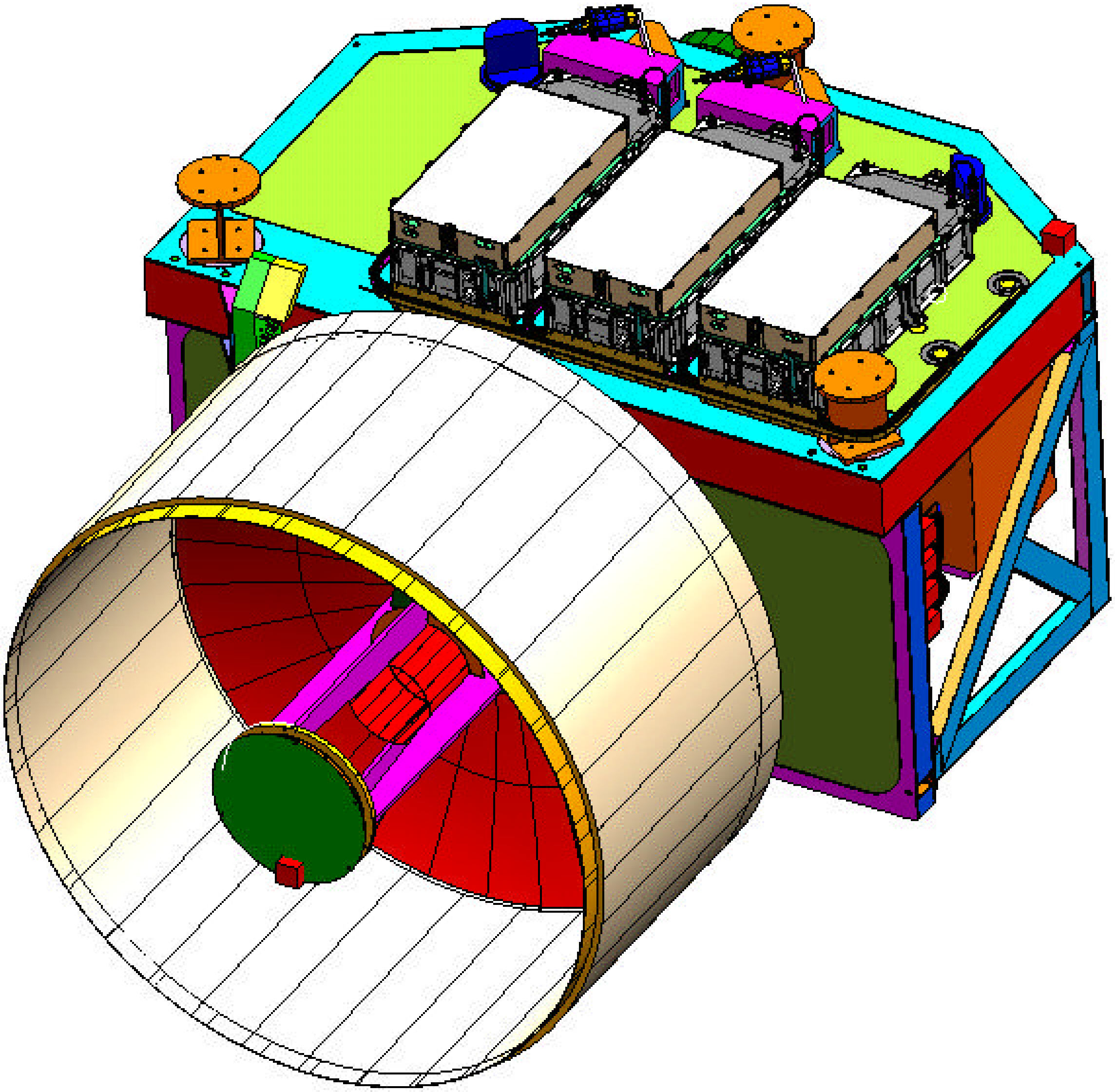


Fig. 1.2.2 Geoscience Laser Altimeter System (GLAS). The one meter telescope in the lower left is surrounded by the Sun shade. The three boxes shown at the top of the drawing represent the lasers. Laser number 1, the rightmost box, will be the first laser operated in orbit. The transmitted laser pulse leaves the instrument at the location just to the upper left of the Sun shade in a direction parallel to the telescope boresight. (Drawing prepared by C. Salerno, GSFC)

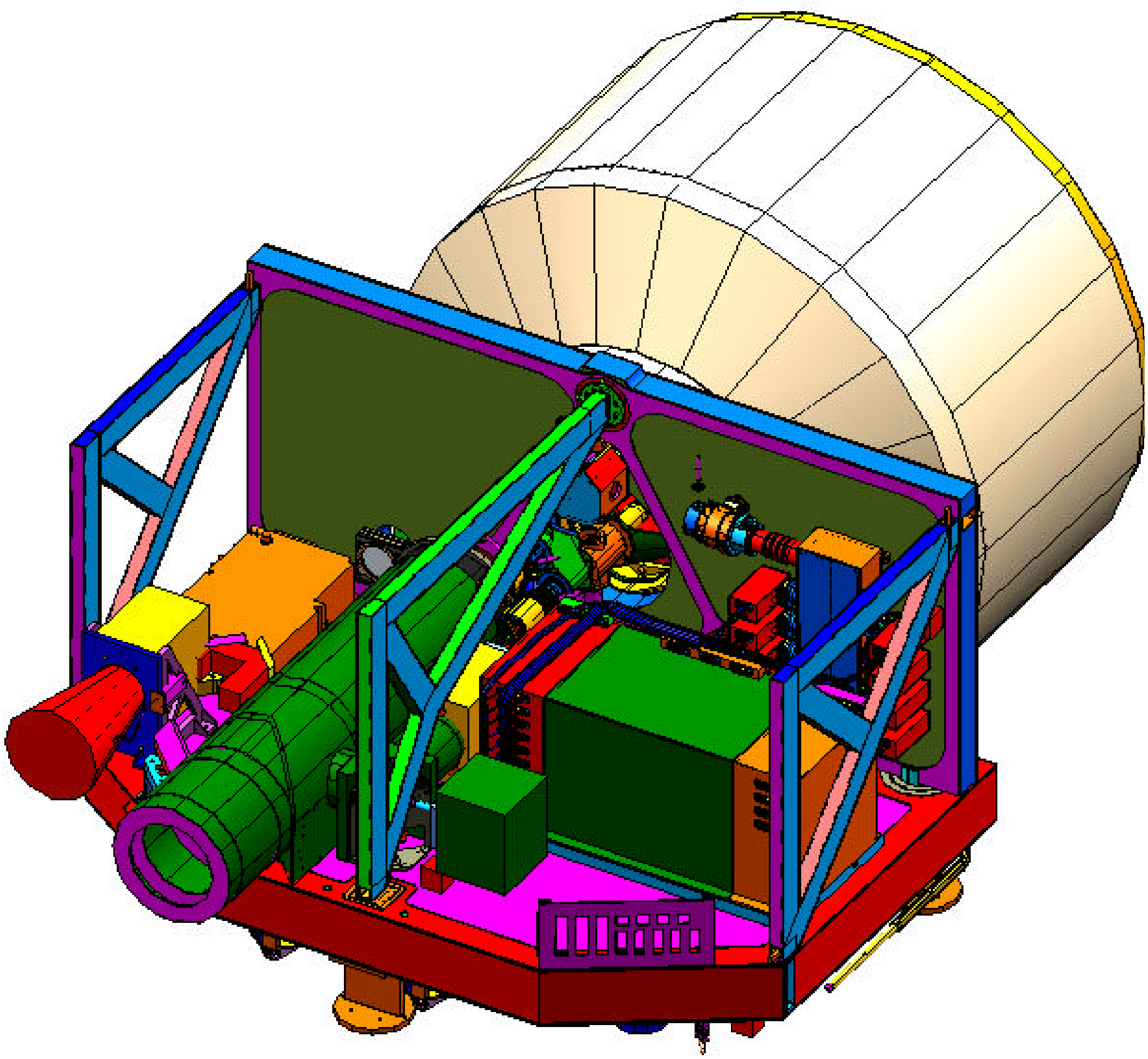


Fig. 1.2.3 GLAS Zenith Side. This view of GLAS shows the SRS, including the LRC, LPA and IST. The SRS is mounted on the optical bench with the lasers. The LRC has a Sun shade, illustrated by the long tube at the left side. The IST uses the smaller shade, illustrated by the conical shape left of the LRC shade. Note that the lasers are mounted on the optical bench just below the LRC and IST in this drawing. (Drawing prepared by C. Salerno, GSFC)

1.2.4 Spacecraft Bus

The spacecraft is being constructed by Ball Aerospace Systems Division in Boulder, CO. The normal orientation of ICESat in space is with the GLAS boresight oriented in the nadir direction, referred to as *nadir pointing*. However, through roll and pitch maneuvers, the spacecraft can point the GLAS boresight off-nadir, referred to as *off-nadir pointing*. Such off-nadir pointing will normally be limited to about 5°.

Two basic orientations are used to minimize yaw maneuvers. In the *sailboat-mode*, the observatory is oriented so that the velocity vector is approximately aligned in a direction parallel to the axis that connects the solar panels to the spacecraft. In the *airplane-mode*, the velocity vector is perpendicular to the solar panel axis. The two orientations are shown in Fig. 1.2.4. The orientation is determined by the position of the Sun with respect to the orbit plane. When the Earth-Sun position vector is approximately contained within the orbit plane, the airplane-mode is used. When the Earth-Sun vector is approximately perpendicular to the ICESat orbit plane, the sailboat-mode is used. When this vector is approximately 33° with respect to the orbit plane, a yaw maneuver is made to transition between the respective orientations. In the airplane-mode, ICESat will experience the longest duration periods of thermal variation associated with solar eclipsing by the Earth. Eclipses also occur in the sailboat-mode, but the duration is shorter.

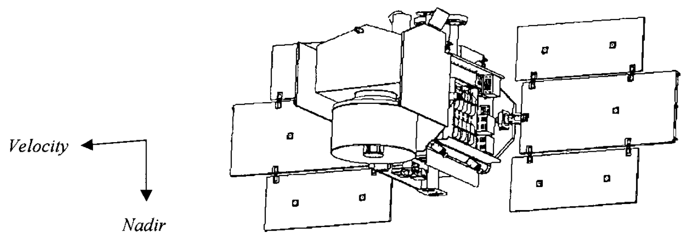
The observatory is a very stable platform for making the precision measurements expected from GLAS. The GLAS optical bench is very rigid and there are few moving parts that can induce undesirable platform oscillations. An oscillation known as *jitter* can be induced by solar array articulation, a motion necessary to optimize generation of electrical power. Stepper motors are used to drive the array and this motion induces natural oscillations of the spacecraft and, hence, the GLAS instrument attached to the spacecraft at the mount locations. To mitigate jitter as an error source, array articulation is inhibited in the polar regions. When inhibited, the expected contribution of jitter to the laser pointing error budget is below 1 arcsec. During articulation, the jitter is expected to be less than 10 arcsec.

1.2.5 GPS Receiver (GPSR)

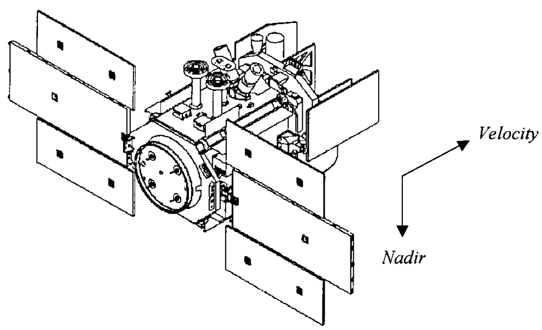
The GPSR for ICESat is the JPL-designed Blackjack based on earlier space versions of the TurboRogue receiver. The receiver is designed to provide GPS dual frequency (1575.42 MHz and 1227.6 MHz) data in the presence of encrypted P-code signals. The GPSR provides an 0.1 Hz clock tick for the time tagging of GLAS measurements.

1.2.6 Laser Reflector Array (LRA)

The LRA closely duplicates the array design used on the Geosat Follow-On (GFO). The GFO array has been thoroughly tested with on-orbit operation. Most ground-based laser range systems provide range measurements with a sub-centimeter accuracy. The LRA is evident in the nadir side of the observatory, shown in Fig. 1.2.1b.



a) Sailboat mode (yaw = 270°)



b) Airplane mode (yaw = 0°)

Fig. 1.2.4. The ICESAT orientations: airplane mode and sailboat mode. These are the nominal observatory orientations which will be maintained for months at a time. Other special orientations are used for short periods (< one orbital revolution) to support orbit maneuvers, for example. The velocity vectors may be in either direction.

1.3 Altimeter Error Budget

The single laser shot error budget for the altimeter-mode is shown in Table 1.3.1. This budget was adopted to meet the cryosphere science requirements, which are given in terms of regional surface change. For example, the science requirement that an accuracy of 1.5 cm/yr be attained in a 100 km x 100 km regions, representing the ice streams of the West Antarctic, for example. For this region, a surface slope less than 1° was assumed for the error budget. It has been further assumed that the laser pointing direction will be determined with an accuracy of 1.5 arcsec. It should be noted that some of the errors are well-characterized by a random distribution, while others exhibit systematic tendencies. In some cases, depending on the time duration, a long period error will appear to be a constant bias. The nature of the errors must be taken into account in the calibration/validation analysis, but for illustrative purposes, no distinction has been made of random vs. systematic in Table 1.3.1. Full scale simulations have been performed to verify the assumed error budget in the table will meet the 1.5 cm/yr requirement.

The GLAS position is obtained from a process referred to as precision orbit determination (POD), which will use the GPS receiver on ICESat in combination with ground-based receivers to obtain the position with 5 cm (1-σ) accuracy. The Earth gravity model is one pre-launch limiting factors so the immediate post-launch period will allow a period for tuning the gravity field and other spacecraft force models, such as the nongravitational forces.

The GLAS laser pointing direction is, in part, dependent on the spatial orientation of the observatory. Determination of this orientation requires a process known as precision attitude determination (PAd). The PAD utilizes star cameras to determine the orientation of the GLAS optical bench. Additional CCD cameras are used to determine the direction of the laser with respect to the optical bench, but this analysis is included in the PAD process. With a 1° surface slope and a PAD requirement of 1.5 arcsec (1-σ), the contribution to the error budget is 7.5 cm.

The troposphere produces a delay of about 2.2 m at zenith, but this a correction can be applied if the surface pressure is known. A 10 mb error in surface pressure produces an error of 2 cm in the applied correction. The atmospheric pressure will be obtained for GLAS using global atmospheric forecasts generated by the National Meteorological Center.

The transmittal of a laser pulse through thin clouds produces photon scattering. Some of the photons are scattered outside the field of view, but some remain within the field of view. Those that remain can follow longer paths. Analysis has shown that path lengthening can be as much as 10 cm. However, use of the GLAS atmospheric channel to identify potential scattering can lead to either data editing for large corrections or an algorithmic correction.

In addition to the error budget shown in Table 1.3.1, there are underlying considerations that are not fully reflected. For the science requirements related to determination of mass balance of the polar ice sheets, which will be inferred from the determination of surface change measurements over extended intervals of time, the important characteristic is the stability of the measurements over the mission lifetime. As a consequence, the long term stability of the altitude measurement is of fundamental importance, which must be a part of the overall Calibration/Validation program.

In a similar manner, the stability of all contributors to the error budget must be validated to eliminate the possibility that they contribute artifacts to the determination of surface change.

Table 1.3.1 Single Shot Error Budget (Altimeter-Mode)

Error Source	Error (cm, 1-σ)
Instrument precision	10
Radial orbit (POD)	5
Pointing (PAD)	7.5
Troposphere delay	2
Forward scattering	2
Other (c.g. location, etc.)	2
RMS	13

Notes:

Pointing error assumes 1.5 arcsec pointing error on 1° surface slope

1.4 Mission Overview

The ICESat is planned for launch no earlier than December, 2001. The immediate post-launch period of approximately 30 days will be allocated to the spacecraft contractor, Ball Aerospace, to verify the operation of the spacecraft. Initial activation of some GLAS components will take place during this period also.

The post-launch period for operations of the GLAS instrument will be divided into four main phases: 1) the spacecraft checkout phase during the first month after launch, 2) the measurement verification/calibration and data product validation phase, spanning less than 120 days after spacecraft checkout and 3) the mission phase, spanning the period after the calibration/validation phase until end of usable spacecraft/instrument life and 4) an interim and/or calibration/validation phase later in the mission. The last three phases can be described as:

• Initial calibration/validation (CV) phase: during this period, specific activities are planned to verify the performance of the GLAS instrument and the spacecraft, which may lead to calibration corrections. As part of this process, the higher level data products will be validated. This period will use a short ground track exact repeat cycle (8 days) to assure frequent overflights of small ground CV sites. Although a variety of CV sites will be used, some of the sites will support both verification/calibration and product validation. The actual duration of short ground track repeat will be determined by the performance of the CV sites. As a consequence, a portion of the mission phase orbit may be considered to be part of the CV phase to ensure compatibility between the short term repeat orbit and the long term repeat used in the mission phase.

• Mission phase: this phase uses a long ground track repeat cycle (0.5 year) with a shorter near repeat subcycle (25 day) to provide a dense sampling on the surface. The subcycle will assure a uniform sampling over a shorter interval to support detection of short period variations. With the longer repeat cycle, the spacecraft will overfly a specific area once (or possibly twice) in a 0.5 year period using nadir pointing, but use of off-nadir pointing will allow more frequent visits.

• Three year/five year CV phases: these CV phases would repeat some aspects of the initial CV phase to evaluate the performance at the end of the three year mission and/or near the expected end of life at five years. While the exact nature of these phases will use the initial CV phase as a model, it is expected that improvements attained over the mission life would be incorporated into these final CV phases. The important aspect of these later CV phases will be to collect data that can be compared with the initial CV phase in meaningful ways to support the characterization of the measurements over the full mission life.

The nature of *in situ* validation is dependent on the particular mission phase. The following sections discuss the characteristics of these phases based on the GLAS orbit (see GLAS Science Requirements, 1997):

Altitude:	~600 km
Semimajor Axis (a):	6978 km
Eccentricity (e):	0.0013 (frozen orbit, with perigee near North Pole)
Inclination (i):	94°

1.4.1 Initial Calibration/Verification Phase

To assure frequent overflights of small CV ground sites, the orbit must repeat with respect to Earth-fixed coordinates with a repeat cycle of about one week. The specific orbit characteristics, represented by mean elements, in the vicinity of a 600 km orbit are:

$a = 6971.5$ km
$e = 0.0013$
$i = 94°$
Repeat interval: 7.989 days (~ 8 days), 119 orbital revolutions

Since a near-polar orbit must be launched from the Western Test Range at Vandenberg AFB, some specific orbit characteristics can be defined. Various factors, not specifically related to ICESat, led to the selection of a 16:00 to 17:30 (Pacific Standard Time) launch window. The launch will take place using a Delta-II vehicle. The at-launch orientation of ICESat will be the sailboat mode. Transition to the airplane mode will occur approximately 3 months after nominal launch.

As noted in the GLAS Science Requirements [1997], the ground track should repeat to within 1 km at the equator. Because of the orbital decay associated with atmospheric drag, the ground track will diverge from the ideal reference. As a consequence, orbital maneuvers (thrusts) will be required to maintain the orbit by raising the semimajor axis to compensate for drag. These drag-compensation maneuvers are expected to occur with a frequency of about 5 days during the early phases of the mission when solar activity is high (2001). The off-nadir pointing capability provides an additional capability to enhance the ability to more accurately repeat specific ground tracks. Off-nadir pointing control will enable pointing to a reference ground track with a 1-σ pointing accuracy of about 30 m.

As noted in the GLAS Science Requirements [1997], the ICESat should be "synchronized" with one of the MODIS platforms to support atmospheric science. The characteristics of these platforms (EOS-AM and EOS-PM) are:

EOS-AM (Terra) has 10:30 a.m. descending node (10:30 p.m. ascending node)
EOS-PM (Aqua) has 1:30 p.m. ascending node (1:30 a.m. descending node)

With the prescribed launch window, the synchronization periods between ICESat and either MODIS platform will not occur during the adopted post-launch calibration/validation period. Assuming a 6 p.m. (local time) launch, the orbit ascending node occurs at 6 a.m. (local time). But the ascending node location changes by 0.5°/day westward with respect to the Sun. As a consequence, the ICESat ascending node will coincide with the EOS-AM node about 7-8 months after ICESat launch. Coincidence with the EOS-PM node will occurs several months later.

For the 8-day repeat orbit, the ground tracks over the continental U.S. are shown in Fig. 1.4.1. In addition, the ground tracks over Antarctica are shown in Fig. 1.4.2 and those for Greenland are illustrated in Fig. 1.4.3. It should be noted that the tracks are consistent with launch from Vandenberg, but the node location has been assumed to provide overflights of White Sands (NM) and Bonneville (UT), as described in a later section.

The locations where the tracks intersect, or *crossovers*, are ideal calibration/validation sites since both ascending passes and descending passes occur at these locations. Furthermore, as noted above, such sites would provide verification for both day and night conditions as well as enabling two opportunities every 8-days. Table 1.4.2 shows the geodetic latitudes where crossovers occur during the 8-day repeat cycle. The longitude of the crossovers is dependent on the node location that is selected to assure overflights of specific locations.

It should be noted that the crossover locations and specific ground tracks are influenced by the orbit parameters. If, for example, the inclination is 93.9° instead of 94°, the orbit semimajor axis would need to be lowered by 0.2 km to obtain the 8 day repeat orbit. Similarly, if the inclination is 94.1°, the semimajor axis would need to be raised by 0.2 km.

1.4.2. Mission Phase

The long repeat cycle of 0.5-yr precludes effective use of small verification sites at specific geo-

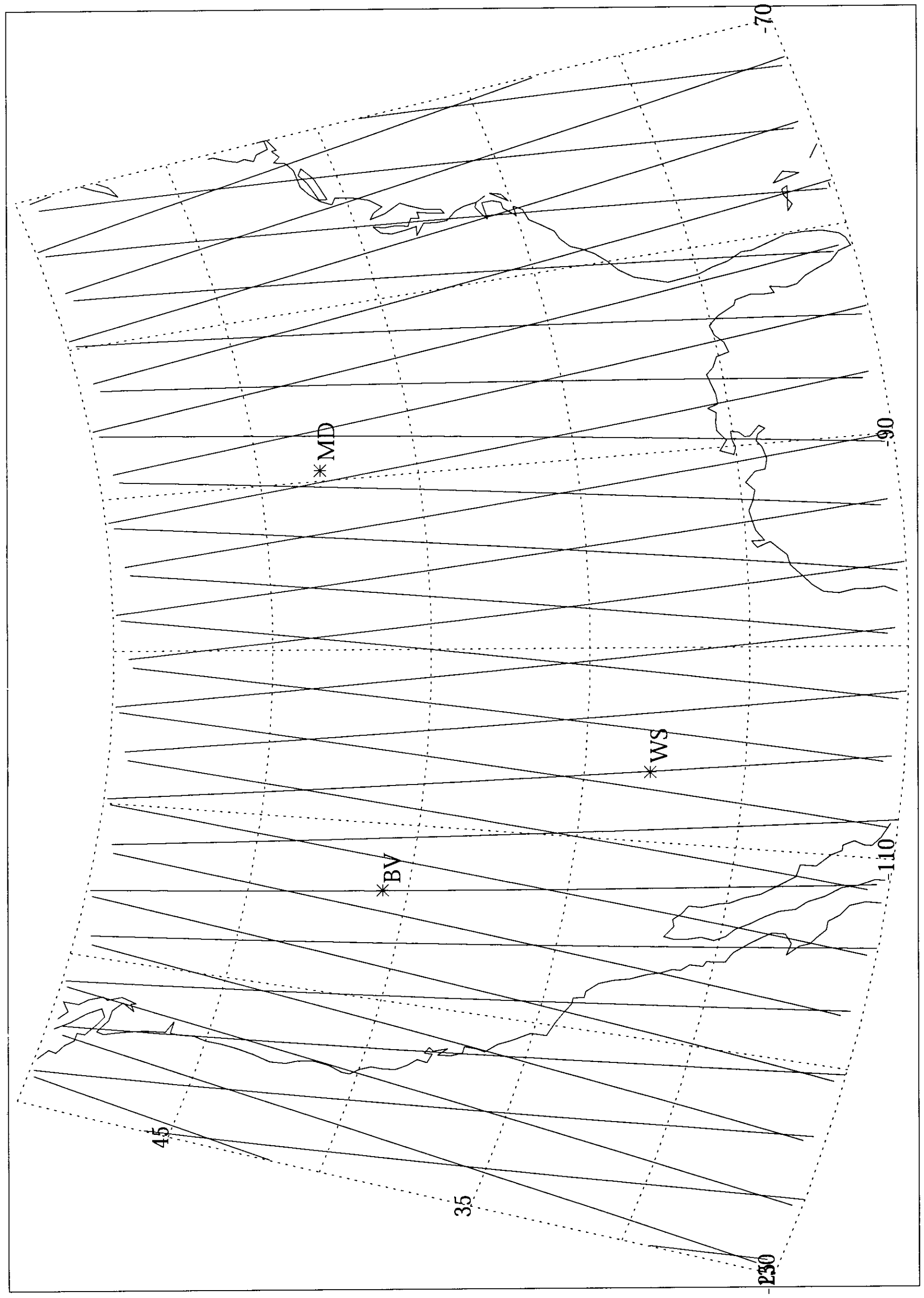


Fig. 1.4.1. 8-day repeat orbit tracks over U.S. The locations noted are: BV-Bonneville (UT); WS-White Sands (NM); MD-Madison (WI)

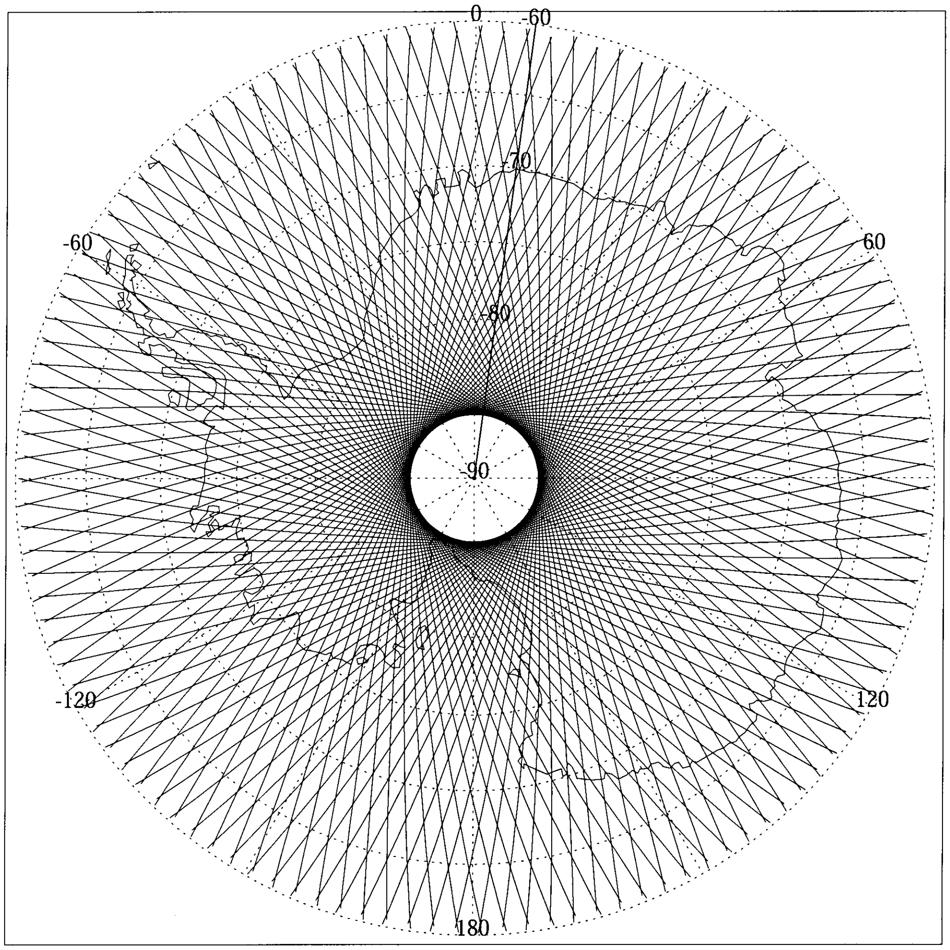


Fig. 1.4.2. 8-day repeat orbit tracks over Antarctica.

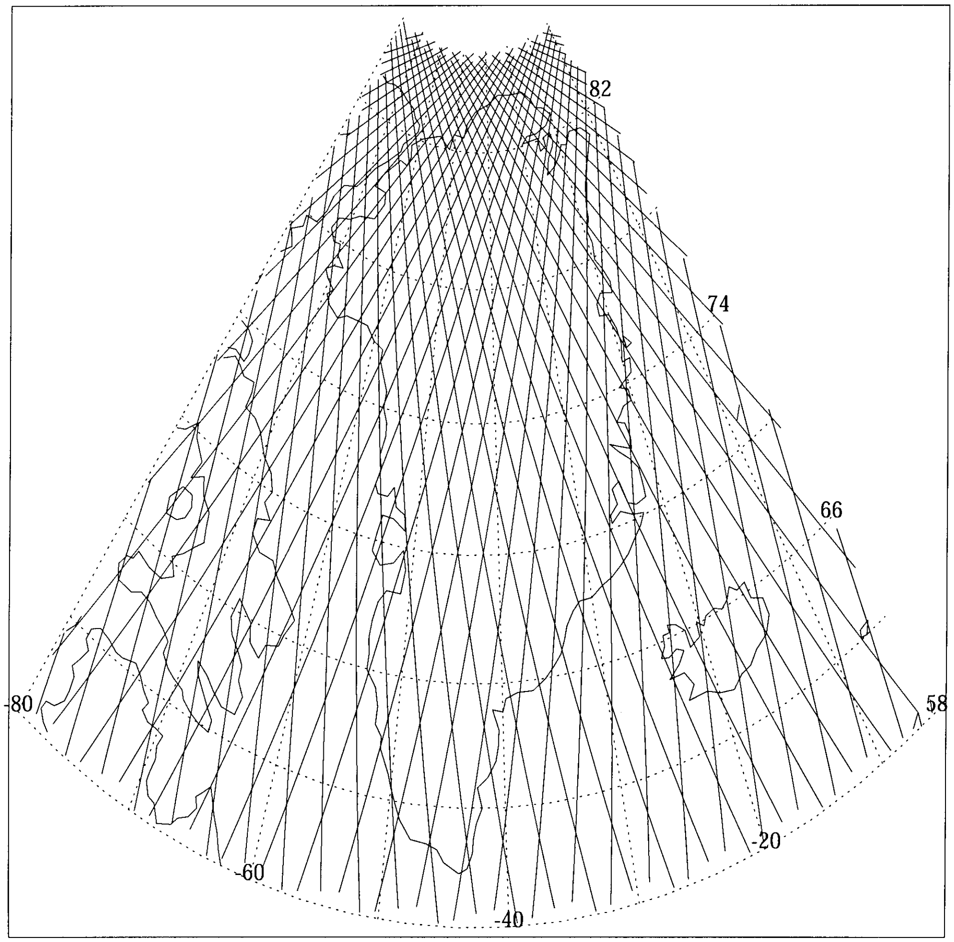


Fig. 1.4.3. 8-day repeat track over Greenland.

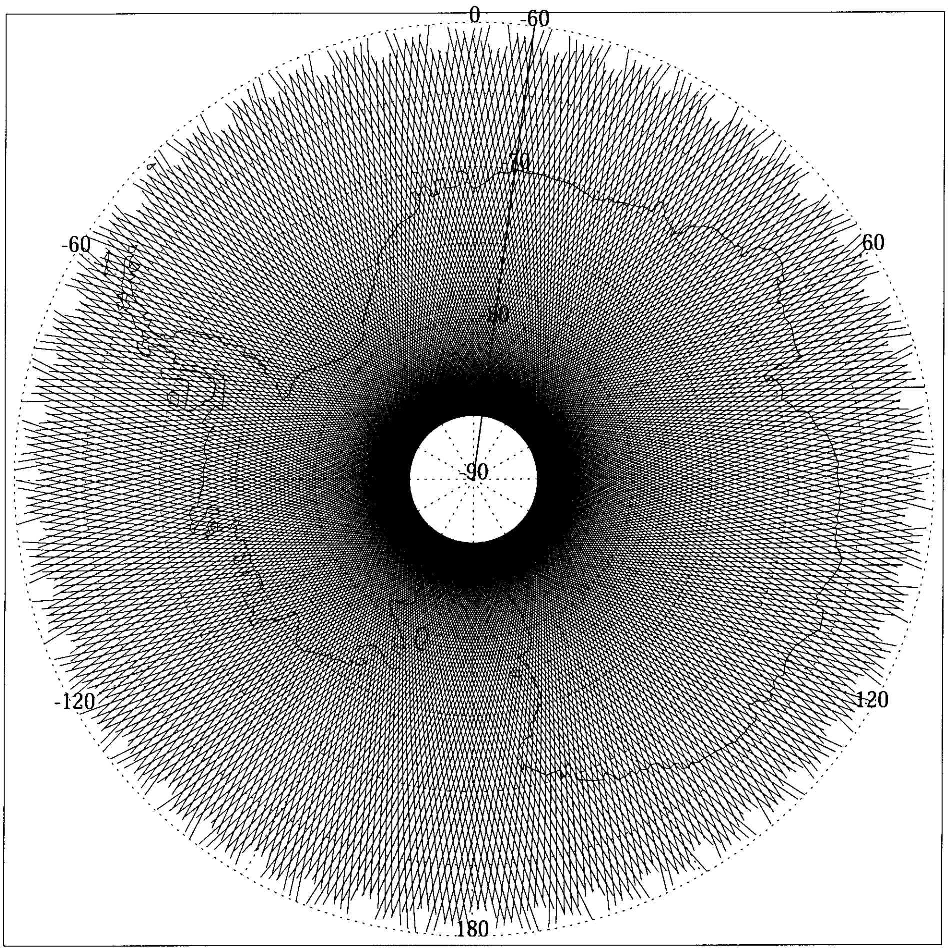


Fig. 1.4.4. 25-day near repeat subcycle from 183-day repeat over Antarctica.

graphic locations if direct overflights are required. In this repeat cycle, the track separation will be about 15 km at the equator; therefore, specific sites will be overflown no more than twice (crossover point) during the 0.5-yr cycle. Most sites will be overflown once on either an ascending or descending pass. The 0.5-yr repeat cycle is designed to include a 25-day subcycle which results in a near-repeat between subcycles. The first 25-day subcycle from the 0.5-yr repeat is shown in Fig. 1.4.4. The next 25-days can be visualized by simply rotating the ground track pattern about the south pole by the equivalent of 15 km at the equator. The specific orbit characteristics for the 0.5-yr orbit are (represented by mean elements):

a = 6970.0 km
e = 0.0013
i = 94°
Repeat interval: 182.758 days (~183 days), 2723 revolutions

The orbit evolution within a 25-day subcycle is summarized in Table 1.4.2. This table provides the time and location of the equator crossings, both ascending and descending, that occur within a 1° longitude band. For passes in the same direction, the interval between successive tracks is usually 25 days with the tracks migrating westward. As the tracks migrate outside the western edge of the 1° band, they reappear at the edge of the eastern boundary after 8 days. These characteristics are a factor in the planning of CV activities.

1.4.3 Ongoing CV

Calibration/Validation activities are not confined to the initial 150 days after launch. It is essential that CV be performed regularly throughout the mission. In addition to routine CV, special efforts will be needed when a change in the instrument or spacecraft configurations occur. Furthermore, special repeats of the immediate postlaunch CV will be appropriate later in the mission, but on a smaller scale. For example, an appropriate time to repeat the early CV phase would be the completion of the three year mission. This repeat would provide a focussed assessment on instrument changes that have taken place during the three year flight, thereby providing a sound basis for characterizing the data quality and reliability. This repeat of the initial CV may or may not require the use of the initial 8 day repeat orbit, but the spacecraft design has sufficient fuel margin to allow such a transition. If the five year mission goal is reached, a similar consideration for repeat will be considered at that time. Furthermore, a focussed CV activity should be conducted if the instrument or spacecraft exhibit signs of imminent failure.

Table 1.4.1 Geodetic Latitudes of Crossovers Between ±80°:
8 day Repeat Orbit

N	S
79.73	-79.73
79.07	-79.07
78.31	-78.32
77.45	-77.45
76.44	-76.44
75.26	-75.26
73.87	-73.87
72.21	-72.21
70.20	-70.21
67.77	-67.78
64.77	-64.79
61.07	-61.09
56.48	-56.52
50.83	-50.88
43.97	-44.04
35.85	-35.95
26.56	-26.67
16.31	-16.45
5.46	-5.60

Note: There are approximately 44 additional crossover latitudes between 80°N and 86°N and a similar number in the range between 80°S and 86°S.

Table 1.4.2 Orbit Evolution Within a 1° Longitude Band at Equator:
183 day repeat cycle

Time (days)	Longitude of Equator Crossing (°)	Approximate Off-Nadir Angle (°)*
1.38	0.06 D	-4.2
9.36	0.99 D	5.6
17.85	0.44 A	-0.2
34.32	0.86 D	4.2
42.82	0.31 A	-1.6
59.30	0.73 D	2.9
67.79	0.18 A	-3.0
84.26	0.59 D	1.4
92.75	0.04 A	-4.5
100.74	0.97 A	5.4
109.23	0.46 D	0
125.71	0.83 A	3.9
134.20	0.33 D	-1.4
150.68	0.70 A	2.5
159.17	0.20 D	-2.8
175.64	0.57 A	1.2

A: Equator crossing is ascending (south to north)
D: Equator crossing is descending (north to south)
*Assumption: nadir overflight at 109.23 days, longitude = 0.46°; + is east, - is west

1.5 GLAS Standard Data Products

The GLAS Standard Products are summarized in Table 1.4.1. These products include several ancillary products required for the generation of the primary products.

Table 1.5.1
GLAS Standard Data Products

Identifier	Description	Product Level
GLA00	Instrument packet file	0
GLA01	Altimetry data file	1A
GLA02	Atmosphere data file	1A
GLA03	Engineering data file	1A
GLA04	SRS and GPS data file	1A
GLA05	Waveform-based elevation corrections file	1B
GLA06	Elevation file	1B
GLA07	Backscatter file	2
GLA08	Boundary layer and elevated aerosol heights file	2
GLA09	Cloud height for multiple layers file	2
GLA10	Aerosol vertical structure file	2
GLA11	Thin cloud/aerosol optical depth file	2
GLA12	Ice sheet products file	2
GLA13	Sea ice products file	2
GLA14	Land products file	2
GLA15	Ocean products file	2
ANC01	Meteorological data	1B
ANC02	Operational orbit and attitude	1B
ANC03	Laser tracking data	1B
ANC04	IERS polar motion and Earth rotation	1B
ANC05	Magnetic and solar flux data	1B
ANC06	Metadata and data product quality	1B
ANC07	Coefficients and constants	1B
ANC08	Precision orbit data	1B
ANC09	Precision attitude data	1B
ANC10	GPS tracking data	1B
ANC11	Miscellaneous	1B
ANC12	Digital Elevation Model	1B
ANC13	Geoid	
ANC14	Pole Tide Model	
ANC15	Earth Tide Model	
ANC16	Load Tide Model	
ANC17	Ocean Tide Model	
ANC19	Surface Type	

2.0 CALIBRATION/VALIDATION CRITERION

2.1 Objectives

The validation process requires knowledge of the measurement characterization and the geophysical quantities being extracted from the measurements. Such knowledge must cover the range of possible conditions over which the measurements will be made. The overall process should establish the uncertainties in the geophysical products being produced and the extent to which the products meet the established science requirements.

In the immediate postlaunch period after GLAS activation, the CV objectives are:

- verify the on-orbit performance of GLAS and the spacecraft to meet the measurement requirements. This verification process will use the prelaunch tests conducted on the instrument and spacecraft as the expected on-orbit performance level.
- determine calibration corrections from the on-orbit data for application to the prelaunch values
- validate the science data products. This validation process uses results from the verification and calibration processes.

The fundamental objective is to validate the science data products to ensure, within time and budget constraints, that appropriate geophysical interpretations can be drawn from the products. The identification and removal of nongeophysical artifacts from the data is an important element of the CV process. If such artifacts cannot be removed, a level of geophysical uncertainty that can be attached to the data products must be established. An unstated, yet nevertheless important aspect, is that the entire process must be done under conditions that will ultimately allow the ICESat data to be compared with data from future missions.

2.2 On-Orbit and Spacecraft Considerations

With the adopted orbit characteristics, the frozen orbit produces an altitude variation that is primarily a function of latitude. The altitude variation for the 183-day mission repeat orbit is shown in Fig. 2.2.1, which shows the minimum and maximum altitude as a function of latitude, where the altitude in this plot is geodetic altitude above the reference ellipsoid. Considering the range of latitudes, the maximum altitude occurs at 86° S (626 km) and the minimum altitude is 597 km at about 14° N. With respect to Earth topography, the absolute minimum altitude occurs at Mt. Everest, about 588 km. The calibration/validation activities should verify the instrument performance at or near the altitude extremes to assess the existence of an altitude-dependent measurement bias.

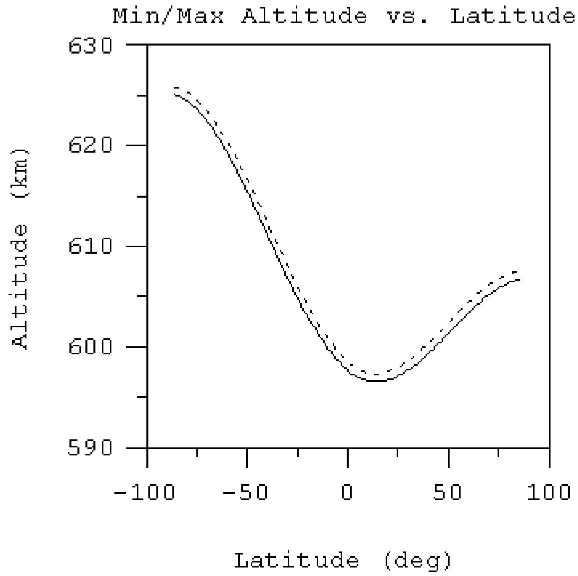


Fig. 2.2.1 ICESat ellipsoidal altitude variation. The two lines illustrate the altitude variation for all latitudes. The minimum altitude at a specific latitude is shown as the solid line and the dashed line shows the maximum altitude.

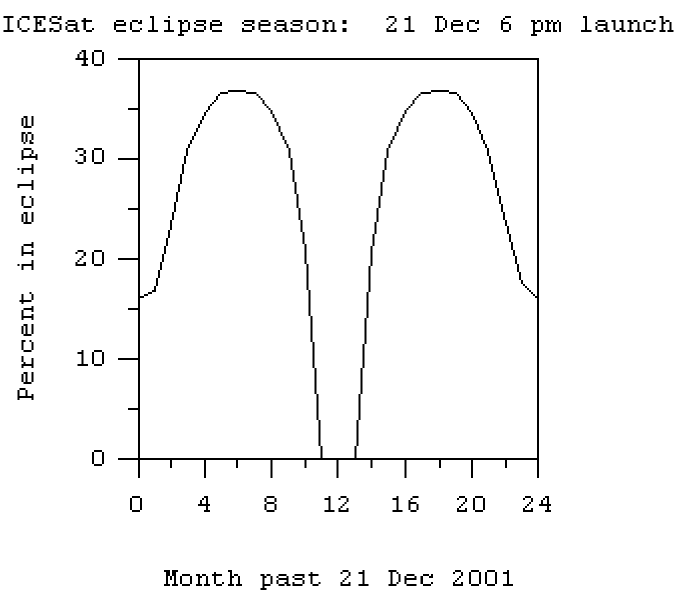


Fig. 2.2.2 ICESAT eclipse season. Launch date was assumed to be 21 December 2001, 6 p.m. local Vandenberg time. The figure shows the percent of each orbital revolution spent in the Earth's umbra. Note that the eclipse-free period repeats every two years since the ICESAT ascending node moves westward from the Sun with a rate of about 0.5°/day.

As noted previously, the preferred launch time is within a window from 16:00 to 17:30 (Pacific Standard Time) at the Western Test Range (Vandenberg AFB). To simplify the following discussion, assume the launch time is 18:00, which produces a 6 a.m. local time ascending node. The ICESAT eclipse season for this assumed launch date and time is shown in Fig. 2.2.2. It is evident from the figure that the CV phase will occur within the eclipse season. Since eclipsing is a major factor in the determination of thermal variations, the eclipse season needs to be factored into the development of CV plans. With a launch on December 21, 2001, Ball Aerospace will check out the spacecraft for about 30 days. It follows that initial GLAS altimeter returns could occur at the end of January, 2002. For purposes of this plan, the start of the CV phase begins about February 1, 2002, and continues through June 21, 2002.

The yaw orientation of the spacecraft is determined by the angle, β, between the ICESAT to Sun position vector and its projection on the orbit plane. Fig. 2.2.3 illustrates the temporal change in this angle for an assumed launch date of December 21, 2001. The yaw orientation will change when $\beta = \pm 33°$. The at-launch orientation of the spacecraft will be sailboat mode (Fig. 1.2.4). From Fig. 1.2.4, the changes in yaw orientation will occur on the following approximate dates:

April 5, 2002 - change from sailboat mode to airplane mode
September 5, 2002 - change from airplane mode to sailboat mode
April 5, 2003 - change from sailboat mode to airplane mode
September 5, 2003 - change from airplane mode to sailboat mode

Both sailboat and airplane orientations will be used during the CV period. There are two considerations associated with these orientations: 1) the orientation of the laser spot as it impinges the surface and 2) the affect of the orientation on POD and PAD. As a consequence, verification data collected early in the CV period may have different characteristics than data collected later in the CV because of the different orientation. The possible influence will need to be verified.

In addition to the preceding changes in orientation, which are motivated by the generation of electrical power from the solar arrays, the spacecraft orientation will change to support orbit control. The spacecraft illustrated in Fig. 1.2.4 clearly shows the thrusters on deck facing the viewer in the upper figure (low β). In the sailboat mode, for example, the thrusters are never pointed in the correct direction for maneuvers designed to offset drag; hence an attitude maneuver is required for all orbit adjustments.

The primary source of spacecraft jitter, which contributes to the error budget of the altimetric mode through errors in laser pointing knowledge, is solar panel articulation. The articulation of the solar panels is driver by stepper motors that have a tendency to introduce jitter. To reduce the effects of jitter, articulation will be inhibited in the polar regions. Thus, mid-latitudes will be influenced by articulation-induced jitter. When the observatory is eclipsed, the solar panels continue to articulate to track a fictitious Sun. As required, the articulation can be inhibited to support CV activities. In any case, one aspect of CV should be to assess the contribution of articulation-induced jitter. Experience has shown that thermal effects on the solar panels may cause them to “snap” at entry and exit into the Earth’s shadow, thereby introducing spacecraft oscillations. However, the spacecraft design is believed to minimize this effect. Nevertheless, it is an additional factor to consider in CV. The spacecraft bus will inhibit articulation for latitudes higher than 50°. As a consequence, this source of jitter is a concern for only the mid-latitudes.

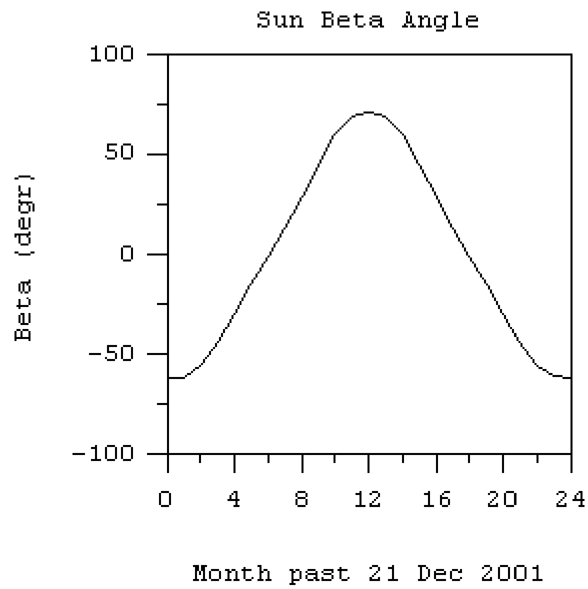


Fig. 2.2.2 ICESAT β angle. The angle describes the orientation of the Sun with respect to the ICESAT orbit plane and it is the primary factor that determines the ICESAT orientation. The spacecraft is yawed to either airplane mode or sailboat mode when $\beta = \pm 33°$.

A consideration for CV will be the manner in which the spacecraft operates in nominal nadir pointing and off-nadir pointing. In general, off-nadir pointing will be used in the polar regions to follow a reference ground track. In other regions, except where commanded to use off-nadir pointing, the ICESAT observatory will operate with geodetic nadir pointing. The off-nadir command sequence will be constructed on the ground and uploaded daily to the spacecraft computer. The commands will utilize a predicted ephemeris for the satellite. In the case of geodetic nadir pointing, the real-time GPS ephemeris will be used to determine the nadir direction. The performance of both nadir-pointing and off-nadir should be assessed during the initial CV phase.

2.3 Instrument Configurations

During on-orbit operations, changes in the instrument configuration will require verification that GLAS is meeting performance requirements. Specific instrument configuration changes include the following:

- Change in operating laser (e.g., switch from laser number 1 to laser number 2)
- Change in the return signal detector (two detectors for altimetry)
- Change in the oscillator/digitizer (two units available)
- Change in GPS receiver/antenna (two units available)
- Elimination of individual SPCM detectors in the atmospheric channel

CV efforts are required to verify the instrument performance with each change in instrument configuration. As appropriate, new calibration corrections may result that are applicable only to the specific configuration.

2.4 Overall Altimetry Cal/Val Approach

As noted previously, it is difficult to separate and validate some of the different GLAS error sources. For example, to verify the altitude measurement made by GLAS, the on-orbit position of GLAS (POD), the laser pointing determination (PAD) and the corrections for propagation delay (troposphere, scattering) must also be known. Hence, even the verification of the instrument performance becomes a data product validation task. Nevertheless, some CV approaches can be designed to minimize the influence of some contributions. Furthermore, there is no single CV approach that can address all contributors under the variety of global conditions in which the instrument will be operated.

The specific items to be verified and/or validated for the altimetry mode are:

- Altitude measurement from GLAS, based on the laser pulse time of flight
- Time tag of the altitude measurement from GLAS (surface arrival time)
- Long term drift in the reference oscillator, which contributes to the determination of the laser pulse time of flight and the time tag, i.e., a long term drift a measured altitude bias
- Determination of GLAS reference point position in ITRS[1] (POD)
- Determination of GLAS laser pointing direction in ITRS (PAD)
- Correction for tropospheric delay
- Correction for surface change (solid Earth tides, post-glacial rebound)
- Correction for forward scattering
- Surface slope/roughness

The orbit, environmental and spacecraft conditions that will be factored into the CV approaches were described in Section 2.2 and 2.3. These are:

- Existence of an altitude-dependent range bias
- Thermal influence on the measurements
- Effects of yaw changes on the measurements
- Effects of solar array induced jitter
- Effects of pointing from two different commands: nadir and off-nadir

The changes in instrument configuration that must be accommodated in the CV plans are:

- Change in operating laser
- Change in operating altimeter detector
- Change in operating oscillator/digitizer
- Change in GPS receiver/antenna

1. ITRS: International Terrestrial Reference System, an Earth-fixed system, origin is coincident with the Earth center of mass

Additional CV activities include the cross-calibration, or alignment, of the Instrument Star Tracker with the Bus Star Trackers. Such cross-calibration is necessary to ensure the use of the BST in the event problems with the single IST occur.

All approaches for CV in this document utilize regional surfaces to support the CV process. These surfaces include flat surfaces (e.g., salt flats and bodies of water), undulating surfaces (e.g., dunes) and rough topography. Although no surfaces are truly static because of atmospheric pressure loading and expansion with moisture, it is convenient to define a static surface to be one with essentially no horizontal motion and vertical motions below a specified threshold. A dynamic surface will be defined to be one with significant horizontal and/or vertical motions, exceeding a specified threshold.

A flat surface is one example where some errors can be minimized to facilitate the determination of range bias. With a flat surface (e.g., a salt flat), the contribution of pointing error to the range is small. For example, with the altimeter range vector oriented perpendicular to a flat surface, the contribution to range with errors in pointing knowledge are 3 mm with 20 arcsec pointing error and 10 mm with 40 arcsec. With the requirement that pointing knowledge be attained to 1.5 arcsec, it is evident that this type of surface can tolerate much larger errors and still support a high accuracy determination of range bias. It should be noted, however, that such determination requires sufficient accuracy from POD and the other factors, notably tropospheric delay and forward scattering. In addition, the location of the flat surface must be known with respect to the same Earth-fixed, Earth-centered reference frame used for POD. This requirement further illustrates the inherent coupling between the various contributions and the CV process. Clearly, the accuracy of range bias determination will be limited by the accuracy of the available POD and the accuracy of other range corrections. Determination of temporal change in the range bias for a particular laser will be related to the drift in the reference oscillator used to measure the round trip pulse time.

As noted in the previous paragraph, the reference surface used in the CV must be geodetically characterized in the same reference frame used for POD. This characterization will be done using 1) ground-based kinematic or static GPS surveys and 2) airborne laser altimetry, which also uses GPS to provide geodetic control.

The ocean represents another flat surface that has been well-characterized and studied using radar altimeters, such as TOPEX/POSEIDON. Aside from anomalies in the surface that are not adequately represented by some models (e.g., ocean trenches), the surface has considerable variability in terms of wave height and meteorological effects over 1000 km distance scales. The response of the GLAS 70 meter spot to ocean waves is an additional factor to be considered.

2.5 Sampling Requirements

Although the immediate postlaunch CV phase is fundamentally important to verify the on-orbit instrument performance as compared to the prelaunch characterization, this CV phase serves other purposes as well. With the recognition that no CV activity can sample continuously and with limited resources to conduct CV, it follows that judicious selection of methodology and techniques is important. Nevertheless, the full characteristics of any technique may not be fully understood until the analysis of the data begins. As a consequence, an important role of the initial CV period is to enable an assessment of the variety of techniques and methodologies that will be applied to the on-orbit verification/calibration of GLAS and the data product validation. The ability to resolve different results obtained by the techniques will be of paramount importance, but the opportunities to apply these different techniques will lend credence to the results.

While the initial CV phase is important, it is crucial to continue the CV activities for the full lifetime. This is the only way to ensure that there are no long term instrumental drifts that may masquerade as temporal changes in the surface, which would produce incorrect geophysical interpretations.

Range Bias

Aside from the importance of verifying the prelaunch characteristics of the range measurement, other factors must be considered:

• Range bias altitude dependency - As discussed previously, the altitude is latitude dependent, ranging from a minimum of about 595 km to a maximum of 626 km (with respect to the ellipsoid; the absolute minima is about 588 km over Mt. Everest). With the use of several flat surfaces at different latitudes, for example, this dependency can be resolved. Such “flat” surfaces follow the curvature of the Earth and they are essentially normal to the local geodetic vertical within a GLAS spot. Furthermore, the dependency can be regularly evaluated by repeating the measurement over the mission life. Candidate sites include:

- Amery Ice Shelf(71°S): 624 km
- S. Argentina (50°S): 617 km
- Salinas Grandes (30°S): 608 km
- White Sands (33°N): 599 km
- Bonneville (41°N): 600 km

Range bias can also be inferred from GLAS measurements over sloping and undulating terrain that has been independently mapped. Candidate validation sites include:

- Dry Valleys, Antarctica
- Simpson Desert, Australia
- Desert regions of Saudi Arabia
- Various arid sites in the Western U.S.
- Northern Greenland

After the use of such sites in the initial 120 day CV phase, the altitude dependency measurements should be repeated regularly (6 months to 1 year). For the initial CV phase, several sites are desirable, but the ongoing maintenance may require fewer sites.

• Range bias dependency on temperature and other factors - Prelaunch testing of GLAS will include thermal variations. This thermal characterization will be used to apply corrections to the on-orbit data based on temperature sensors in the instrument. Nevertheless, CV experiments should be constructed to evaluate the potential influence of unmodeled temperature effects, especially those that may result from the on-orbit environment. Likewise, an error in the radial component of orbit position will be absorbed into an estimate of the range bias, so the CV plans should minimize the orbit error over the CV site through the use of separate, but localized measurements and/or techniques.

• Range bias change with time - A range bias change with time relates directly into the determination of surface change, which makes the determination of such dependency especially important. Such change may occur with aging of the laser, for example. In principle, the repeated use of flat surfaces as described above would provide the basis for monitoring the temporal variation. Initial CV efforts should examine the short term variation (few days to weeks), but the determination of changes on time scales of months will be important. The GLAS oscillator is used to measure the round trip time of flight, but the oscillator drift will masquerade as a geophysical surface change so it is essential to provide experiments to unambiguously monitor the range bias.

Time Tag

The time tag assigned to the GLAS measurements is derived from a quartz oscillator within GLAS, which is linked to GPS time through an 0.1 Hz clock pulse generated by the GPSR. The GPS time system is based on atomic clocks maintained by the U.S. Naval Observatory. Drift in the oscillator occurs with aging, but temperature variations will produce short term changes. The error budget in Section 1 provided an overview and implicitly assumed the error was small. But this assumption must be validated since an error of 1 ms, for example, would infer that the laser spot is displaced by 7 meters horizontally, thereby producing an error similar to the pointing error.

Laser Pointing

The IST and the gyro system will be used to determine the orientation of the GLAS optical bench with respect to the International Celestial Reference Frame. In turn, the LRC and the LPA provide the direction of the transmitted laser pulse with respect to the optical bench. To the extent that the instrument mounts are rigidly attached to the optical bench, possible pointing direction biases can be expected to exist as the result of alignment changes, especially during the vibrations during the launch phase. During post-launch periods, the alignment may change with thermal variations. Although changes in the characteristics of the CCDs used in the IST, LRC and LPA can be expected to occur over their lifetime, the primary instrumental change will be thermally driven, which is primarily the result entry/exit events into the umbra/penumbra (eclipse region). The gyros are well know to exhibit biases, but these biases are determined during the normal mode of operation where the gyros and IST are combined in the attitude determination process.

The time tag of the various instruments used to determine the laser pointing direction depends on both the GLAS oscillator and the oscillator carried on the spacecraft bus. Drift in both oscillators occurs with time, but each is latched to the 0.1 Hz clock pulse generated by the GPSR.

3.0 PRELAUNCH INSTRUMENT CHARACTERIZATION

Prior to launch, the Instrument Team has responsibility for development and testing of the GLAS instrument, as well as establishing the prelaunch baseline of the instrument characterization. This prelaunch baseline will be used as the starting point for verification of instrument performance in the postlaunch phase.

3.1 Altimeter

In early 2001, the three flight lasers were tested in the Space Lidar Technology Center laboratories. The laser characteristics measured in the laboratory are summarized in Table 3.1. The mounted lasers are shown in Fig. 1.1.2 and the rightmost box in this figure corresponds to slot number 1 in Table 3.1, which is the first laser to be activated in flight and uses only fixed optics in the transmit path. Table 3.1 shows that although the flight laser closely meet the specifications, the lasers have some different characteristics. These different characteristics underscore the need to conduct CV experiments for each laser.

Testing of the fully assembled GLAS instrument began in mid-2001. Environmental testing began in Fall 2001. From the CV viewpoint, the following pre-flight measurements will provide calibrations that will be the starting point for on-orbit instrument verification:

- the correction to be applied to time of flight measurements to adjust the measured range to a specific, identifiable point on the instrument (e.g., a point on the optical bench). This correction must be determined empirically since measurement of the optical paths to determine the time delays is difficult and prone to error.
- the temperature dependency of this correction
- the alignment of the IST, LRC and the LPA; that is, determine each boresight direction with respect to instrument axes and optical bench axes, as shown in Fig. 3.1
- the temperature dependency of the IST, LRC and the LPA alignment
- the relation between the outgoing laser beam and the illuminated pixels in the LRC, to enable determination of the laser beam direction with respect to the stars defined in the ICRF
- characterize the stability of the reference oscillators and their long term drift

3.2 Algorithm Testing

The implemented algorithms have undergone testing at ISIPs (Hancock and Brenner, 2001).

Table 3.1. Selected Flight Laser Test Results.

Characteristic	Specification	Laser Slot 1	Laser Slot 2	Laser Slot 3
Serial Number	N/A	2	3	1
Pulse Energy (mJ)	110	113	111	106
1064 nm Energy (mJ)	75	76	77	76
532 nm Energy (mJ)	35	37	34	30
Pulse width (ns)	<6	6.1	6.3	5.8
Divergence (μrad)	110	118	113	68
Far Field Circularity	>0.67	0.70	0.63	0.82
Pointing jitter (μrad)	±11	4	4	5

Wavelength of lasers is very close to specification: 1064.5 nm and 532.2 nm
Slot number represents the nominal order of laser use.
Laser tests conducted at the NASA Space Lidar Technology Center and reported by Afzal (2001).

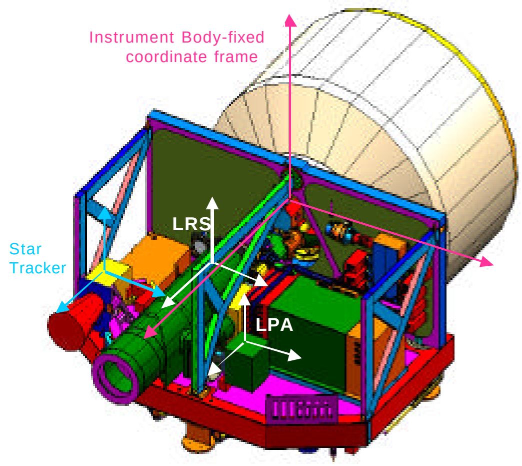


Fig. 3.1. The optical bench reference axes and the axes used with the IST, LRC and the LPA.

4.0 VALIDATION OF LEVEL 1A PRODUCTS: GLA00 AND GLA01

4.1 GLA00

The raw data transmitted from GLAS are represented by GLA00. A separate plan for validation of these data will be prepared.

4.2 GLA01

The GLA01 data products are a reversible transformation of the raw data, GLA00, into engineering units. A separate plan for validation of Level 1A will be prepared, except for selected products given in the Section 5 of this report.

5.0 POST-LAUNCH CAL/VAL ACTIVITIES FOR LEVEL 1B PRODUCTS

5.1 Non-instrument corrections

The generation of surface topography profiles from altimeter measurements requires the following non-instrument corrections:

- ANC08: Knowledge of the position of a reference point within the GLAS instrument, expressed in an Earth-centered reference system,

- ANC09: Knowledge of the location of the laser footprint on the Earth's surface, determined by knowledge of the laser pointing direction. This direction is primarily dependent on the spacecraft attitude, expressed in the Earth-centered reference frame used for describing the position (ANC08),

- ANC11: Atmospheric delay corrections to the altimeter range measurement and corrections to account for known temporal variations of the Earth's surface, such as solid Earth tides.

5.1.1 Precision Orbit Determination (ANC08)

The determination of the precise position of the GLAS instrument, expressed in a global geodetic reference frame, will be performed using two independent sources of data. The first data source is provided by the Global Positioning System (GPS) receiver carried with the GLAS instrument. The second is based on data acquired by the ground-based satellite laser ranging (SLR) system using the laser reflector carried with GLAS. The GPS data are represented by ANC10 and the SLR data are represented by ANC03. In addition to the GPS data collected by the receiver carried with GLAS, a ground-based GPS data set is required also. The extensive network of the International GPS Service for Geodynamics (IGS), which contains more than 100 permanently operating GPS receivers, will meet the GLAS needs.

Information on the IGS can be obtained from http://igscb.jpl.nasa.gov; the current network includes more than 200 stations, with good global distribution. The IGS GPS data and information about the SLR network can be obtained from the NASA Crustal Dynamics Data Information Service (CDDIS). Both the IGS and the CDDIS monitor the quality of the data collected by the respective GPS and SLR networks. The GPS ground data as well as the flight data from the GLAS spacecraft are represented by data product ANC10, but these data simply represent the data from the various receivers formatted into the accepted international standard, RINEX. The SLR data are represented by ANC03, which consist of time and the range measurement, as well as other information such as local meteorological data.

The GPS and SLR data will be used to determine the orbit, as described by the Precision Orbit Determination Algorithm Theoretical Basis Document (ATBD) [Rim and Schutz, 1999]. The validation of ANC08 is described in the following.

5.1.1.1 Validation

The validation of ANC08 will be conducted using several approaches, based on separate use of the GPS data and the SLR data. The GPS data offers significant flexibility and it is the only tracking data available while the GLAS spacecraft flies over the major ice sheets, since no SLR stations are positioned near Greenland and Antarctica. This flexibility provides for two ways of determining the GLAS position in space:

- Dynamic determination and reduced dynamic approaches as demonstrated for TOPEX/POSEIDON [e.g., Schutz, et al., 1994; Yunck, et al., 1994]
- Kinematic determination, which has been widely used on aircraft applications with high precision positioning requirements [e.g., Krabill, et al., 1996], and which is independent of the description of the satellite force environment.

The dynamic approaches will require improvements in the gravity field and atmospheric drag modeling. These improvements will be made during the initial verification phase, but the approaches have been demonstrated with TOPEX/POSEIDON and with high fidelity simulations [e.g. Davis and Schutz, 1996].

In addition to the GPS approaches, the SLR data provides a significant alternative. However, there are several considerations with the SLR approach. First, the number of available SLR stations in the post-2001 time period is uncertain, but it is expected that the number of millimeter-level precision stations will be small, probably about 20. Secondly, the cost of operating the SLR network may inhibit 24 hour per day operation, although ongoing developments toward automation may be achieved to reduce SLR operation costs. Third, the SLR network cannot track every possible pass because of priority tracking conflicts and/or clouds. Nevertheless, the SLR data provide a powerful means of validation, as demonstrated by TOPEX/POSEIDON. With these considerations, an intense period of SLR tracking would be conducted for a several week period. Outside this period of intense tracking, the SLR data will be used in a different mode to validate the GPS-determined GLAS orbit. The scheduling of the intense SLR period is to be determined, but an additional consideration is that the validation campaign should occur after the force models (gravity and drag) have been improved. Another consideration is that the SLR approach does not allow a kinematic solution and the technique must rely on dynamic approaches which rely on accurate modeling of the forces acting on the spacecraft.

Two periods of intense tracking of the GLAS spacecraft using SLR are planned, each for a duration of several months. The first period would occur during the initial verification phase while the second period will take place during the first year of the main mapping phase. The SLR data acquired during the initial verification phase will be used, along with the GPS data, to improve the gravity field and atmospheric force model. Since the data collected during this verification phase would be used to “tune” the gravity field, a validation period during the main mapping phase is necessary to complete the validation process. SLR data during the entire mapping phase will be used to validate the GPS-determined orbit by computing and analyzing SLR residuals.

In addition to the determination of the GLAS orbit using different data types, the orbit can be determined using different software packages using the GPS data as well as the SLR data. The existing, independent software packages that meet the needs for GPS and SLR determinations are:

- MSODP/UTOPIA: University of Texas package

- GEODYN: Goddard Space Flight Center
- GIPSY: Jet Propulsion Laboratory

Although various experiments have been carried out to verify these packages at the sub-centimeter level, the low altitude environment used by GLAS suggests the need for processing the tracking data with more than one package. While the regular processing over the mission duration may be done with one package for the standard product, the validation will be performed at regular periods with one or more additional package. It is anticipated that all three packages will be used during the verification period and at least two of the packages will be used during the main mapping phase.

5.1.2 Precision Attitude Determination (ANC09)

Direct validation of the precision attitude determination (PAD), represented by ANC09, is difficult to accomplish because of the limited independent sources of observations: star camera and gyro data. While comparisons with independent determinations, such as those obtained to support the spacecraft flight operations, the disparity in accuracy will prevent definitive conclusions. The real time attitude requirement is on the order of 10 arcsec while the PAD requirement is 1 arcsec. Nevertheless, comparisons between the real time and PAD results will identify major discrepancies.

The definitive validation of the PAD will be accomplished with the validation of the data products representing the three-dimensional coordinates of the laser spot location and the time series of the coordinates. The latter time series reflects a profile of the surface topography. In the pre-launch period, star camera data collected on other satellites, such as XTE (X-Ray Timing Experiment), will be studied as a means of better characterizing the error sources.

5.1.3 (ANC xx) Tropospheric Delay

Partial validation of the troposphere delay will be performed by comparison of the extrapolated atmospheric pressure from the NMC at validation sites with actual measured values. Further validation will be conducted with measurements from the verification sites.

5.1.4 Other

Validation of solid Earth tide corrections will be accomplished at the verification sites. Furthermore, evaluation of pulse stretching from forward scattering will be validated with data from the verification sites.

6.0 MEASUREMENT VERIFICATION AND VALIDATION OF LEVEL 2 PRODUCTS

6.1 Overview

The verification/calibration of the instrument and validation of the data products must be conducted throughout the mission. Nevertheless, one of a kind CV experiments are important to add further credence to the characterization of the data products. The apparent emphasis placed on the initial CV phase is justified for the following purposes:

- immediate postlaunch verification of the instrument performance, as determined by the prelaunch characterization,
- encourage multiple techniques to be applied to the CV problem and understand the limitations and error sources of the techniques, and
- identify the techniques to be regularly used over the mission life and those that may be applied at intermittent intervals.

All CV techniques applied must have a responsible person who maintains the experiment and ensures the proper analysis of the acquired data. For the most part, the current activities are funded by the Science Team budget, with some in kind contributions from other sources, e.g., the Instrument Team. The responsible person is a member of the CV Working Group, which has the responsibility to ensure coordination and reduce unnecessary team duplication in CV.

With multiple techniques applied to the verification problem, it is especially important to understand the errors associated with the technique. As a consequence, all techniques must be sufficiently well understood to ensure their use as a standard for the verification of GLAS measurements and the validation of the data products. It is important that the techniques provide consistent and accurate results.

Since changes in instrument configuration can be expected to occur over the mission lifetime, such as switching lasers or detectors, some of the techniques must be able to support verification of the instrument performance in the new configuration. Other techniques may be used only intermittently. The long repeat cycle of 183 days poses challenges for the verification since nadir overflights of a site will occur once every 183 days in the same direction.

6.2 CV Working Group Coordination

The Working Group will foster not only coordination of the activities of each team, it will provide a forum towards understanding the error sources that contribute to the cal/val activities. The following workshops are planned to promote team coordination:

• *Early prelaunch readiness workshop*: this workshop will take place in the fourth quarter of 2000 for the purposes of a) discussing plans of the instrument team for prelaunch calibrations and b) reviewing the science team readiness for postlaunch verification and data product validation. The specific plans of individual cal/val teams that are provided in the subsequent sections were reviewed at this workshop.

• *Preliminary prelaunch readiness workshop*: this workshop will take place in second quarter of 2001 for the purpose of reviewing results of the prelaunch calibration. This workshop will provide the prelaunch calibration results which will be subsequently verified in the postlaunch cal/val phase. Updates of individual team readiness for the postlaunch activities will be reviewed at this workshop.

• *Prelaunch readiness workshop*: this workshop will take place in fourth quarter of 2001 for the purpose of making final preparations for postlaunch cal/val prior to launch. All teams will report their readiness to participate in cal/val activities.

• *Initial postlaunch workshop*: this workshop within about one month after initial on-orbit measurements from GLAS. This initial postlaunch workshop will address early verification results and on-orbit instrument performance. This workshop will also address plans for the remainder of the cal/val phase and make adjustments to the plan based on the instrument/spacecraft performance and characterization.

• *Cal/val workshop 1*: this workshop will take place approximately midway into the planned cal/val phase, approximately 60 days after initial measurements from GLAS. The purpose will be to obtain an assessment of the instrument/spacecraft performance midway into the cal/val phase. At this workshop, review and comparison of results from various cal/val techniques should be conducted and the differences resolved or understood. Possible requests to change prelaunch calibration constraints will be discussed and referred to review by the Calibration Change Control Board. At this workshop, consideration will be given to the scheduling of the orbit adjustment into the 183-day mission repeat cycle.

• *Cal/val workshop 2*: this workshop will take place near the end of the scheduled cal/val phase, approximately 120 days after initial measurements from GLAS. The purpose of the workshop will be to review all results from the cal/val phase, establish the completion date of the cal/val period and start of the mission phase. At this workshop, the final results of the postlaunch cal/val phase will be presented and final recommendations made to the Calibration Change Control Board will be made for the mission phase.

• *Annual cal/val workshops*: workshops that address ongoing cal/val activities should be held at least annually during the mission phase. Events, however, may warrant convening a workshop at any time to address specific questions or performance issues. The workshop should be viewed as preparation for submittal of changes to the Change Control Board for the data processing procedures that involve calibration corrections.

6.3 Calibration Change Control Board

The Calibration Change Control Board (CCB) will be established for the purpose of formally reviewing and adopting changes to the prelaunch calibration constants or the inclusion of new correction factors. The CCB membership will include members of the science team, the instrument team and some with no direct affiliation with GLAS.

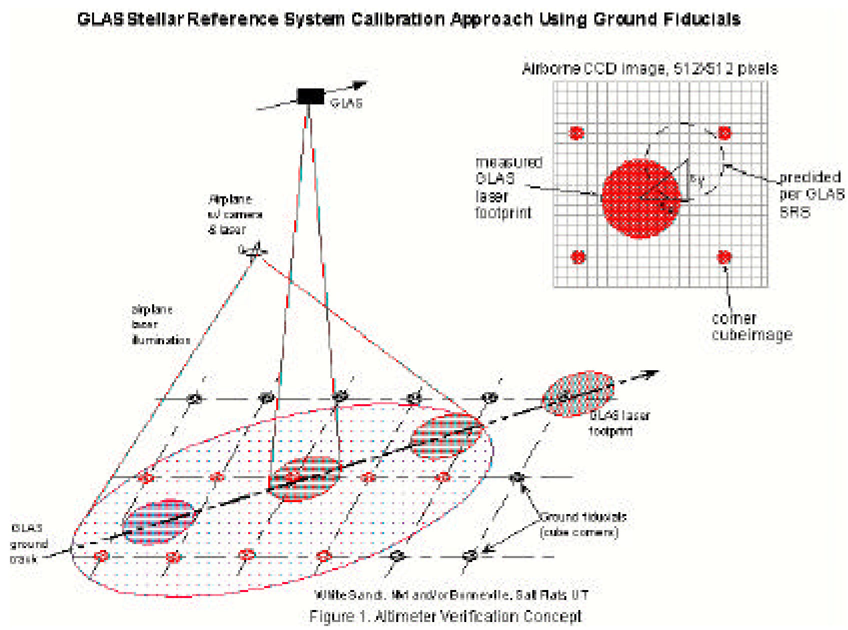


Fig. 6.4.1 Imaging GLAS footprints at White Sands/Bonneville

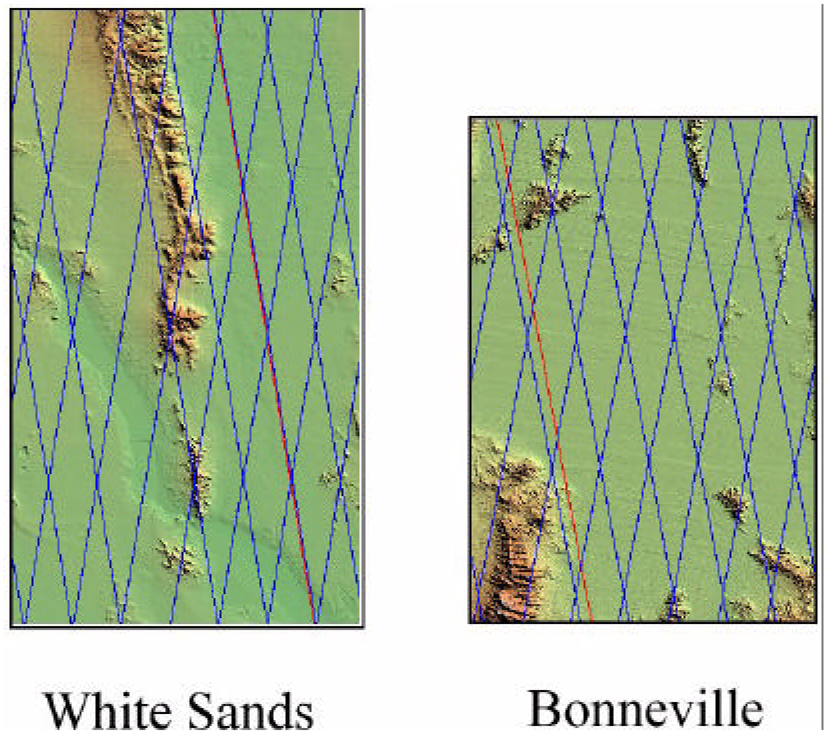


Fig. 6.4.2 Ground tracks for overflights of White Sands and Bonneville. The tracks shown represent the 183-day repeat cycle. A single track representing the 8-day repeat cycle is shown in red (for Bonneville, it is the track offset slightly to the right; for White Sands, the track coincides with a 183-day track, so it appears as a solid line). Figures created by Helen Fricker.

6.4 In Situ Laser Spot Imaging and Detection

Concept

The imaging of GLAS laser spots on a flat surface, such as a dry lake bed, provides a means of directly verifying and validating different components of the system. In concept, an image of the laser spots during the brief interval of the spacecraft overflight of a CV site provides an independent means for determining the spot coordinates, provided that the spot locations can be determined with respect to the same terrestrial reference frame used for the generation of the GLAS data products that infer surface profiles. The image can be made using appropriate instrumentation, such as a CCD camera positioned above the CV site, such as an aircraft, or with an array of detectors. In the latter case, the array of ground-based detectors are analogous to CCD pixels and each detectors position will be known in the same terrestrial reference frame as the GLAS-inferred products. In the CCD image case, ground fiducial reference points will appear in the image to establish the spot coordinates in the appropriate terrestrial reference frame. With the operation of GLAS in the nadir direction (or very near nadir), the altitude measurement will be verified.

An important aspect of the postlaunch CV phase is to compare the results from the two methods. Both methods will be used over the mission life, but it is desired to reduce the frequency of the airborne measurements. The methods are illustrated in Fig. 6.4.1.

The NASA shuttle landing facility located at White Sands Missile Range (WSMR), New Mexico, was selected as the primary location for the conduct of the experiments. A backup site at Bonneville Salt Falts will be used. Discussions have been conducted with cognizant WSMR officials regarding the experiment and with Bureau of Land Management officials with Bonneville responsibility. The overflight tracks are illustrated in Fig. 6.4.2.

The aircraft overflight approach is illustrated in Fig. 6.4.1. A CCD camera will be carried by a State of Texas Cessna 206 aircraft, which has been configured with an observation port in aircraft underside. The aircraft overflight will be timed with the overflight of GLAS to enable imaging of several GLAS spots. These experiments are planned to take place in darkness to reduce the considerable noise introduced by sunlight. With the 6 p.m. launch time and the ground track oriented to overfly White Sands on an ascending pass, the at-launch overflights will occur at 6 a.m. local time. Since the ICESAT orbit plane moves westward with respect to the Sun, the overflights will occur 1 hour earlier every month. As a consequence, White Sands overflights will occur at 5 a.m. one month after launch and 4 a.m. two months after launch, for example. The aircraft will also carry a laser to illuminate the fiducial markers, planned to be constructed from highly reflective Stimsonite. The resulting CCD image will show the GLAS spot and the reference points, where the positions of the reference points will be determined using ground-based GPS positioning to provide centimeter-level accuracy coordinates.

With ICESAT travelling at 7 km/sec, the White Sands CV overflight duration will be less than one second. Since the single engine Cessna 206 travels about 90 m/sec, the aircraft overflight requirement can be stated to allow 10-20 sec flexibility in arrival time before the spacecraft. The instrumented grid with fiducial markers will be about 3-4 km long (in the ICESAT along-track direction) and about 400 m wide (in the cross-track direction). The spacecraft overflight can be predicted days in advance to better than one second accuracy, there is considerable margin for the aircraft arrival and stationkeeping operation. Nevertheless, time of arrival experiments intended to simulate the GLAS overflight were initiated in August, 2000, and will be continued through December, 2000.

In the second approach, an array of detectors will be placed on the ground to emulate a camera. The detectors will be placed in a grid pattern, with about 20 m separation between the grid points. The minimum grid size required to capture one footprint is about 200 m (along-track) by 400 m (cross-track). The detectors are designed (Magruder, 2000) to trigger at two intensity levels. These two levels will be set according to the laser intensity expected at the center of the laser pulse and toward the edges of the pulse. The triggering will be indicated by an illuminated LCD on the circuit board and each detector will be checked after the overflight. The illumination characteristics will be recorded and analyzed to determine the laser spot location. The nature of the detectors allows their operation under both day and night conditions. Successful laboratory tests with detector prototypes have been conducted at the University of Texas at Austin and at Goddard Space Flight Center.

A subset of the detector array will be used to validate the measurement time tag. By attaching the subset to a computer configured with a GPS timing receiver, the pulse time of arrival will be determined. To facilitate the identification of the specific spot that triggered the detectors (and timing units), the timing array will be augmented with laser cube corners erected on poles of different heights. These cube corners will ensure a unique waveform characteristic, with respect to those collected in the nearby vicinity, thereby allowing unambiguous identification of the spot in the GLAS data stream. The time tag verification will verify the time to an accuracy better than 0.1 ms.

Both the detector array and the layout of fiducial targets will be planned to enable determination of the laser pointing direction to the 1.5 arcsec level, or 4.5 meters on the surface. This requirement will determine the separation distances between the respective detectors and fiducial targets.

A third approach will use the Level 2 profile to assess the temporal surface change. Large dry lakes, such as the Great Salt Lake Desert, salar de Uyuni (Bolivia) and other sites. The Bolivia site is under investigation by Bruce Bills (private communication, 2001). Over such an area measuring 100 km x 100 km, crossover measurements can be used to validate the data products where small variations in the surface are expected.

Organization

This approach is a collaboration between the Science Team, represented by B. Schutz (University of Texas at Austin/Center for Space Research), and the Instrument Team, represented by J. Abshire (Goddard Space Flight Center). Participation at the respective institutions include:

- UT-Austin
  - Eric Silverberg: airborne CCD development
  - Lori Adrian Magruder: ground-detector development
- GSFC

- Marcos Sirota

Some portions, such as the characterization of the surface using kinematic ground GPS is done in collaboration with the GLAS Science Team of Bernard Minster, UCSD, with development by Helen Fricker.

Validation Products and Sampling

By using a flat surface, which can be easily characterized, the CV concept will provide verification of:

- laser measured altitude
- laser pointing measurements
- measurement time tag and GLAS oscillator drift

and validation of the following data products and corrections:

- POD
- PAD
- stellar reference system for determination of laser pointing with respect to the spacecraft
- tropospheric correction
- solid Earth tide correction
- other corrections, including corrections to the altimetry from scattering.

Potential operating environment effects on the GLAS data products will be evaluated. These effects include:

- thermal contributions
- spacecraft jitter
- offnadir pointing effects
- yaw orientation (airplane mode and sailboat mode).

Error Budget

Operation of GLAS in a nadir pointing (or very near nadir) direction enables a direct verification of the altitude measurement. In this pointing direction, the sensitivity of the computed altitude used to verify the instrument performance is small, thereby allowing a direct assessment of the measured altitude. The sensitivity to offnadir angle and pointing knowledge error is illustrated in Table 6.4.1.

Table 6.4.1 Sensitivity to pointing errors with flat surfaces

Offnadir Angle (°)	Pointing Knowledge Error (″)	Magnitude of Range Error (mm)
0	36	10
0.01	15	10
0.1	2	11
0.1	10	56
1	1	56
5	1	280
5	2	560

Table assumptions: no orbit error; flat surface.

Although Table 6.4.1 assumes the only error is associated with pointing, it illustrates the sensitivity. Using the error budget from Table 1.3.1 to represent expected performance levels and assuming the flat desert surface can be characterized over the region where GLAS measurements will be collected to 2 cm, the verification of altitude measurements is expected to be consistent with Table 1.3.1. In this case, the computed altitude (based on the orbit position, the desert surface elevation model, and other altitude corrections) will be compared with the GLAS measured altitude. The difference between the two quantities will suggest the existence of a bias, or temporal error, in the altitude measurement. Multiple measurements are important during the same pass. For example, if 10 measurements are available (0.25 sec), the various errors can be further reduced by a factor of three. In addition, under appropriate conditions, the errors given in Table 1.3.1 can be reduced. For example, using the SLR system at McDonald Observatory, which can track ICESat during the ascending White Sands overflight, the 5 cm expected orbit error can be further reduced. With ground measurements of atmospheric pressure, the troposphere error will be further reduced. The operational plans at White Sands include a lidar to ensure proper characterization of the atmosphere and to provide information to correct for forward scattering. With these considerations, an altitude bias will be determined with an error expected to be less than 10 cm. An important consideration, however, is that this altitude bias will be based on less than 1 sec of data so multiple overflights are essential to provide a measure of temporal variations and to determine the consistency and stability of the test.

It is useful to summarize the determination of range bias over a flat surface. If the GLAS is operated at near-nadir over the flat surface, then the pointing error (from PAD) is essentially removed under normal operations of attitude control. Given the radial orbit position from POD and an independently derived model of the flat surface, expressed with respect to the same origin as the POD, the computed altitude (distance from origin to satellite minus perpendicular distance from origin to flat surface) can be compared to the GLAS-measured altitude (range). The difference between the measured and the computed is, after removal of the effects in Table 1.3.1 (e.g., troposphere):

- error in the GLAS measurement (usually characterized as random noise)
- error in the radial orbit position from POD
- error in flat surface characterization with respect to the origin
- error in troposphere delay model
- error from forward scattering

If the only error came from the GLAS measurement and a 4 km stretch of flat surface was used, the random nature of the error could be reduced by averaging. With a 10 cm noise and assuming 25 measurements over the 4 km, the effective error would be 2 cm. But if the noise is 5 cm, then the effective error would be 1 cm. Over the 4 km, orbit error will essentially appear as a bias, but there are two ways of reducing the orbit error as discussed in Section 5: SLR and kinematic GPS, but SLR may not always be available. At White Sands, SLR from McDonald Observatory will occur at high elevation, so the SLR ranges will measure a significant part of the radial orbit error. At least in some cases the orbit error can be expected to be reduced to better than 2 cm. Experiments with characterizing flat surfaces using ground GPS suggests that this error could be better than 2 cm (private communication, Helen Fricker, 2001). For such overflights, ground instrumentation will include a meteorological unit to effectively eliminate the troposphere error. Finally, the forward scattering error will certainly be small for some overflights.

In summary, the major error sources for such experiments are likely to be measurement noise, orbit error and surface characterization. If each is at the 2 cm level, then the overall range bias would be determined with an error of 3.5 cm. But other assumptions can reduce or increase this error.

The ground segment to image the GLAS spots on the desert surface or to trigger detectors will provide information to verify the performance of the GLAS Stellar Reference System and Instrument Star Tracker. The spacing of the grid of fiducial marks or detectors is designed to provide positioning of the GLAS spot to about 4.5 meters, or 1.5″. With near nadir pointing, the effective angle of incidence to the surface is small and the error in the troposphere model is negligible. One error source that remains under investigation is atmospheric scintillation; however, preliminary results suggest that this error does not contribute to the error budget. As in the case of the altitude bias, several measurements are required to ensure proper characterization.

If the altitude bias is determined independently of pointing bias as described above, then offnadir pointing can be used to assess the pointing error. The large sensitivity of altitude to a 5° offnadir angle is shown in Table 6.4.1. During the 8 day repeat, the offnadir pointing angle to White Sands in the descending pass (the ascending pass overflies White Sands), exceeds 5°. To support various studies during the initial cal/val phase, offnadir pointing angles up to 5° to flat surfaces are desired. Clearly, the ocean surface can be used as described in the subsequent section that describes ocean scans. Alternatively, a set of candidate sites in Nevada have been identified and will be investigated to determine their suitability. These sites are shown in Table 6.4.2.

A set of sites such as those shown in Table 6.4.2 can be used during the 183-day repeat cycle after a change in instrument configuration. Suppose a switch in laser occurs, which is an event that requires verification/validation as soon as possible. By reviewing the upcoming ground tracks for the next week or two, candidate flat sites can be found for range bias validation. It has been demonstrated that both ground kinematic GPS or small, airborne lidar systems can be used to characterize the surface, which can be performed on short notice. Similarly, deployment of the pointing system based on the airborne camera or ground detectors can be implemented as well.

Table 6.4.2. Candidate Sites for Offnadir Point Experiments

Location	Latitude	Longitude	Offset (Asc)	Offset (Dsc)	Notes
Lunar Lake NV	38°23 N	116°00 W	38 km	40 km	Used by Terra for cal
Railroad Valley NV	38°29 N	115°39 W	69 km	11 km	Near Lunar Lake
Gerlach NV (north)	40°45 N	119°16 W	49 km	*	
Gerlach NV (south)	40°36 N	119°36 W	22 km	*	
Eureka NV (north)	40° N	116° W	62 km	64 km	
Smith Creek NV	39°18 N	117°30 W	77 km	66 km	

* Offset exceeds 100 km

Operational Considerations and Requirements

The technique makes use of detectors and/or fiducial marks laid out in a grid pattern, with the coordinates of each grid point accurately determined with GPS. Tests to lay out the initial grid were successfully performed in Austin by Craig (2000) using kinematic GPS. Conceptually, the grid pattern will be established prior to launch and markers will identify the grid points. Prior to the individual overflights, the detectors and fiducial marks will be implanted at the predetermined grid points and collected after the overflight.

To support verification of the measured altitude by GLAS, a characterization of the surface is required. This characterization is essentially a digital model for elevation in the same reference

LOCATION	TIME Day Hr (local)	OFF-NADIR	Direction	Equipment	PURPOSE
Salt Flat, TX	001 4 PM	5 deg	Desc.	Detector array GPS geodetic	Pointing verif. Range verif +. POD verif.
Truth or Conseq. NM	002 4 PM	1 deg	Desc.	Detector array GPS geodetic	Pointing verif. Range verif. POD verif.
Deming NM	002 4 PM	2 deg	Either Truth or Consequences or Deming, but not both		
White Sands NM	007 4 AM	0 deg	Asc.	Aircraft camera Ground reflectors Detector array GPS geodetic GPS timing Met. package	Pointing verif. Pointing verif. Pointing verif. Range verif. + POD verif. Time tag verif. Range verif.
Salt Flat, TX	009 4 PM	5 deg	Desc	Same as previous Salt Flat	
Truth or Conseq. NM	010 4 PM	1 deg	Desc	Same as previous T or C/Deming	
White Sands NM	015 4 AM	0 deg	Asc	Same as previous White Sands	

NOTE: ground travel between Salt Flat and Truth or Consequences is about 200 miles, about 4 hrs. To use same detectors at both sites, the detectors at Salt Flat would need to be collected after the overflight, but before dark. Transport could allow travel and overnight lodging in El Paso, then travel to T or C the next morning, with setup at T or C starting about noon. Assumes pre-overflight layout of the grid.

Table 6.4.3 Timeline for Cal/Val in the Vicinity of White Sands frame used for the POD and PAD, an ITRF. Two approaches will be used at White Sands and Bonneville. First, the surface will be modeled using kinematic GPS, but this approach will be confined to determination of the coordinates of selected reference points. The variations between the points will not be directly measured, but inferred by visual inspection to establish an approximate rms level. The second approach uses an airborne laser altimeter to provide a detailed digital elevation model of the overflight area. The latter approach is preferred, but is more expensive. Nevertheless, it will be used at least once for comparison with the GPS approach.

The two verification approaches using ground detectors and aircraft imaging will be done simultaneously in the early phases. The advantage is that two independent methods will be used at the same location, thereby enabling direct comparisons. As confidence is gained in the methods, they will be deployed separately, perhaps to different locations to provide broader coverage.

The grid pattern and an overflight track from GLAS will closely coincide during the 8-day repeat orbit cycle. If they do not exactly coincide, requests to the mission operations to invoke offnadir pointing to the grid track will be required. In general, these requests will provide the latitude/longitude tracks that GLAS should be directed to in the overflight. This offnadir approach will also be required during the 183-day repeat orbit.

The overflights will evaluate pointing-induced jitter. This evaluation will be performed by requests to the mission operations center to either invoke or inhibit solar array articulation, the major source of jitter. In principle, comparison of the pointing images under both conditions will provide an upper bound for the effect.

To increase the number of opportunities for pointing direction verification/validation, the airborne camera technique described earlier can be used at both White Sands and Bonneville using the same aircraft and camera. During the 8-day repeat orbit, the overflight sequence is as follows:

- at t=0, White Sands overflight
- at t=48 hrs, Bonneville overflight
- at t=192 hrs, White Sands overflight
- at t=240 hrs, Bonneville overflight

Unless the weather is prohibitive, a ferry flight between White Sands (El Paso) and Bonneville (Wendover) within 48 hours is feasible. Such a strategy would double the number of opportunities within an 8-day period using the same equipment. With the airborne camera, ground support is minimal since about 50 fiducial marks would need to be installed prior to the GLAS overflight. At a secure location such as White Sands, these marks can remain on the ground, but at a publically accessible site like Bonneville, it is advisable that the marks be removed between flights. Nevertheless, the small number of fiducial marks can be deployed in a short period of time.

Nominal Schedule

Consideration has been given to using sites near White Sands on the descending pass to verify the pointing determination using the detector array. Several candidate sites are under consideration, including Truth or Consequences (NM), Deming (NM) and Salt Flats (TX). The timing and logistical considerations are shown in Table 6.4.3.

The first White Sands overflight will focus primarily on acquiring the GLAS footprint to verify the ICESat pointing control and to verify the ground segment instrumentation. The following overflights will focus on verification of the laser measured altitude, the pointing determination and the time tag under conditions without solar array articulation. As soon as possible, the experiments will be expanded to include solar array articulation to assess the jitter effects on pointing.

The 8 day orbit is designed to overfly White Sands. Although the 183-day orbit will overfly White Sands also, the long repeat cycle limits the overflights to one in six months. To accommodate verification over the mission life, and especially following changes in the instrument configuration, the alternate Nevada sites will be used to assess the altitude measurement in near-nadir overflights. The offnadir sensitivity can be used to assess the pointing determination with measurements at White Sands, Bonneville and the Nevada sites.

Archival

The verification data acquired in the ground segment will be archived at the Center for Space Research as well as the GLAS Science Computing Facility at Goddard.

6.5 Other Flat Surfaces

The salar de Uyuni in Bolivia is particularly attractive because of its size. Unfortunately, the 8-day repeat tracks miss the central region, but this salt flat will be very useful during the 183-day repeat since the tracks will be separated by about 14 km and several tracks cross the salt flat in the same direction. This region has been studied by Bruce Bills (private communication, 2001) and is a suitable candidate for GLAS CV.

6.6 CV Concept: Undulating Topography

Overflights of regions of known topography, measured by other means, provide additional means of validating the surface profile measurements. Over a smooth, undulating surface, the measured altitude compared to the predicted will change sign and magnitude depending on the strike and magnitude of the surface slope. Consequently, comparison of GLAS-inferred surface elevations with independent estimates should reveal the magnitude and direction of the pointing error, assuming that it changes slowly with time. Moreover, such a comparison should detect any constant bias between the two sets of measurements, possibly indicative of orbit errors and/or range bias.

The 8-day repeat orbit during the Verification Phase offers the opportunity to validate GLAS performance over well-mapped stripes of terrain of sufficient width to ensure inclusion of the GLAS footprints. Orbit repeat is expected to be within 1 km, requiring a stripe of approximate width 2 km, but with pointing, it should be possible to reduce this to about 0.6 km.

Starting in 1991, NASA has developed, tested and improved the Airborne Terrain Mapper (ATM) for precise surface-elevation mapping, utilizing a scanning laser altimeter and kinematic GPS. This system has been tested for internal consistency, by comparing data from repeat tracks and

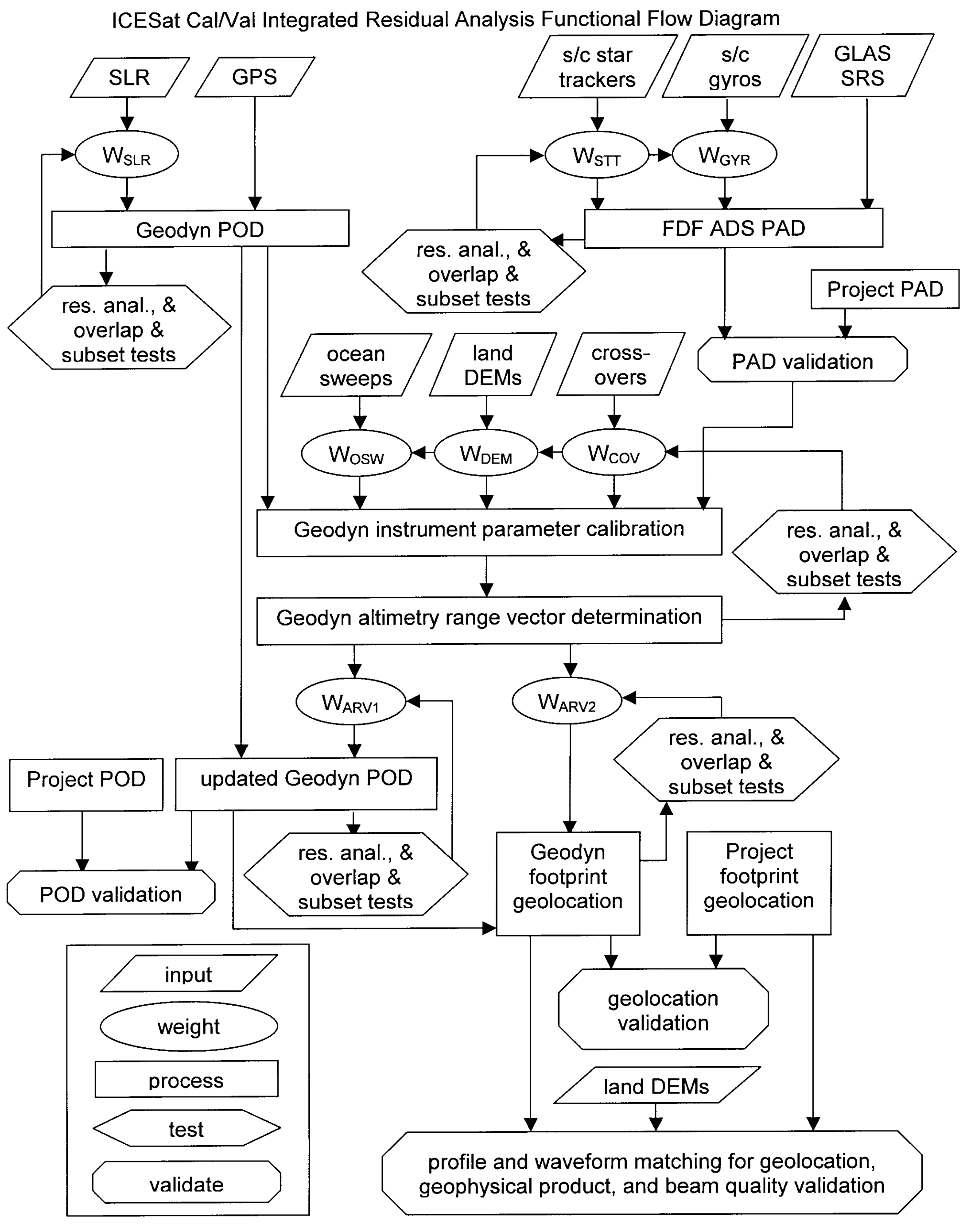


Fig. 6.7.1 Flow Diagram for Integrated Residual Analysis

flight-line crossing points, and overall performance by comparison with independent measurements of elevation along flight tracks [Krabill eta al, 1995a]. The ATM will be used to map “validation stripes” along GLAS orbits during the verification phase, with sufficient parallel, overlapping ATM swaths to map a stripe broad enough to capture the GLAS footprints. At a ground clearance of 400 m, the ATM swath is about 140 meters wide. Consequently, flight lines separated by 100 m would provide a set of swaths with 40 m overlap between adjacent swaths. This allows roll errors to be corrected, with the result that errors in the resulting mapped stripe will be associated with laser-range errors and errors in the kinematic GPS solutions. The slope induced-surface elevation-errors are illustrated in Fig. 6.2.

A candidate site with an undulating surface is the Mali sand dunes in Africa. The “center” of the dunes is at approximately 17.5°N and 7.2°W and the dunes extend for 150 km or more from this location. The 8 day repeat that overflies White Sands and Bonneville on ascending passes also overflies the Mali center on an ascending pass and a descending pass occurs 6.5 km away from the center point. A crossover point occurs nearby at 16.3° N (Table 3.1).

6.7. Integrated Residual Analysis

Integrated Residual Analysis (IRA) is composed of three different calibration and validation techniques. The first technique is based on standard precision orbit determination (POD) solutions that have been expanded to calibrate other parameters of interest. This technique itself integrates three observation types: GPS, ground-based satellite laser ranging (SLR) and the ranges from laser altimetry. The second technique is precision attitude determination (PAD) from star tracker and gyro data. The first technique requires the results of PAD as inputs and can be used to discriminate between various PAD solutions. The third technique, profile and waveform matching to digital elevation models (DEMs), requires as a starting point the accurate parameters which the first two techniques provide. The DEM matching will also feed back into the first two techniques by discriminating between (validating) various expanded orbit solutions and PAD solutions. In the following sections, the three calibration and validation techniques are described. Table 6.7.1 illustrates the connection among the techniques and their relationship to CAL/VAL of the ICESat data products and parameters. Figure 6.7.1 is a functional flow diagram of the entirety of Integrated Residual Analysis.

6.7.1 Introduction

Over the years orbit determination techniques and software packages have been developed for using satellite altimetry observations to simultaneously estimate orbit parameters, attitude parameters, instrument parameters and geophysical parameters. These are largely the same parameters which need to be calibrated in order to accurately geolocate the ICESat mission’s altimetry. It should be noted that the modeling required to geolocate altimetry is a proper subset of the modeling required to estimate parameters from altimetric ranges. GLAS laser altimetry provides a unique link between orbit, instrument, pointing and geophysical parameters.

Other observations from the ICESat mission (i.e., GPS tracking and SLR) can be used to calibrate and validate orbit parameters. Although these two data types are more sensitive to orbit parameters than altimetry, they have no sensitivity to pointing and instrument bias parameters.

Of course, it is possible to calibrate and validate subsets of parameters with single data type solutions. However, single data type solutions are inevitably limited to a small subset of parameters. Solutions that combine multiple data types offer more flexibility than single data type solutions. An entire spectrum of solutions is possible and single data type solutions can be realized within the context of combination solutions by selecting data weights appropriately. Expanded orbit combination solutions will use GPS, SLR and altimetry. The altimetry itself will have different forms: direct altimetric ranges over oceans (ocean sweeps), direct altimetric ranges over land sites with accurate DEMs and altimetric crossovers.

One advantage of single data type solutions is that one data type can be used to calibrate (estimate) parameters and a second data type can be used to independently validate the parameters that have been estimated by the first data type. That, of course, sacrifices the strength of the calibration solution for the sake of validation. Furthermore, validation for combination solution calibrations can be provided by orbit overlap and geolocation overlap techniques as well as independently by the DEM matching described in the third part of this chapter. Calibrations provided by combination solutions are at least as strong as those provided by single data type solutions since single data type solutions can be approximated or even realized by combination solutions.

A methodology will be given for choosing data weights so that the strongest possible combination solution is chosen. Because GPS and SLR are such strong data types for orbit parameter estimation it may turn out that the optimal combined solution has altimetry down weighted with respect to SLR and GPS. That would be equivalent to two separate solutions, one for attitude, instrument and geophysical parameters and the other for orbit parameters. If that it is the case then at least it will have been determined to be optimal and not chosen arbitrarily. Furthermore, the two separate solutions (altimetry and GPS/SLR) will be combination solutions themselves with their internal weights optimally chosen. Also, if there are any problems with the GPS receivers, the altimetry can be up weighted. Finally, even if it is determined that the orbit parameters are best calibrated by completely down weighting altimetry, orbit solutions using up weighted altimetry can be used to validate other parameters determined from altimetry alone. In other words, orbit tests can be used to discriminate between altimetry solutions for non-orbit parameters. Each candidate non-orbit parameter set would be held fixed while altimetry would be used to help determine orbit parameters. The relative quality of the orbits would be a measure of the quality of the other parameters.

6.7.2 Laser Altimetry As a Whole

To facilitate the processing of the laser altimeter range data for the calibration of instrument and orbit parameters and to validate GLAS orbit, pointing, ranging and geolocation products, laser altimeter range model algorithms have been implemented into NASA/GSFC’s GEODYN precise orbit and geodetic parameter estimation system [Pavlis et al., 1998]. The GEODYN implementation allows for the simultaneous estimation of the dynamic parameters of the orbit and the geometric parameters of the laser range measurement model through the reduction of laser altimeter range data residuals. Three laser altimeter measurement models have been implemented within the GEODYN system and all three take into account the motion of the satellite over the round trip light time of the laser pulse. The first model is for geolocation and is not used for parameter estimation. This geolocation model provides for the computation of the final standardized geolocation product and is also used as a starting point for the "dynamic crossover" measurement model discussed further below.

6.7.3 Direct Laser Altimetry

The second GEODYN laser altimetry model is for the "direct altimetry" measurement type. The round trip range is computed using knowledge of the spacecraft position, laser pointing, timing and ranging parameters along with surface height. GEODYN has the capability to ingest multiple surface height grids representing various land areas and the ocean surface. The observed ranges are compared to those computed from the measurement model. The discrepancies between the observed and computed observations (i.e. the residuals) are minimized through the estimation of orbit, pointing, timing and ranging parameters. A detailed discussion of the direct altimetry measurement model and the laser pointing and body attitude parameterization is presented in Luthcke et al. [2000a].

6.4.4 Direct Laser Altimetry Over Oceans (Sweeps)

The direct altimetry range residual analysis capability will be applied to the reduction of open ocean sweep data for the calibration of pointing, timing and range instrument parameters. The ocean sweeps are composed of roll and pitch maneuvers where the spacecraft (and thus the laser altimeter beam) is deliberately pointed off-nadir to increase the angular sensitivity, i.e. the lever-arm, of the range measurement. Open ocean surface elevations are very accurately known, through a host of radar altimeter measurements and intensive modeling, providing a reference surface with global access throughout the mission. A recent paper by Luthcke et al. [2000a] provides the methodology, computational model and the results of a pre-launch error analysis for this technique as applied to ICESat. Luthcke et al. [2000a] evaluate the quality of pointing parameter determination as a function of the maneuver details. They show that the GLAS laser beam pointing angle can be determined to the sub-arcsecond level from a 30 minute calibration maneuver, in which the spacecraft points the GLAS laser beam a maximum of 5 degrees off nadir in a slow, conical-shaped roll and pitch maneuver. The maneuver is illustrated in Fig. 6.7.2. Further analyses by Luthcke have shown that similar performance can be achieved with shorter (~1000sec) octagon shaped maneuvers designed to approximate the optimal conical maneuver while staying within the capabilities of the spacecraft hardware and software. Present plans call for the octagon maneuver to be performed on long passes over the Pacific, constrained to the mid-latitude region. During the CV phase, the maneuver would be performed on an ascending and a descending pass once per day.

In addition to the extensive pre-launch error analyses and simulations performed, this ocean sweep direct altimetry technique has been used to significantly improve Shuttle Laser Altimeter (SLA) geolocation. SLA orbit, pointing and ranging parameters have been calibrated from a combined reduction of tracking and SLA direct altimeter range [Luthcke et al., 2000b]. It is important to point out that GEODYN has the capability to solve for time dependent instrument parameters with higher order terms beyond a simple bias. This was extremely important in the reduction of SLA data since a significant drift and periodic pointing correction were discovered and calibrated. The time dependent parameter and higher order terms beyond a simple bias will enable us to calibrate instrument parameter temporal variations due to environmental influences over the life of the mission. The ICESat simulations reported to date show that the ocean sweep maneuver is capable of producing sub- 5cm range bias solution simultaneously with sub-arcsecond pointing parameter calibration even in the presence of possible significant thermally induced periodic and exponential pointing bias variation [Luthcke, et al., 2000a].

6.4.5 Direct Laser Altimetry Over Land

As mentioned previously, the direct altimetry measurement model implementation within GEODYN facilitates the use of any gridded input surface to serve as the reference surface. Thus, applying the same measurement model as used for ocean sweeps, direct altimeter range residuals will also be evaluated against calibration site topography represented by a DEM. In a similar fashion as the ocean sweeps, minimization of range-residuals for GLAS profiles across very accurate DEMs of high spatial resolution will be used to contribute to the calibration of instrument parameters and the validation of GLAS ice and land elevation measurements. The DEMs will be constructed from independent high precision and resolution airborne and ground based measurements. Use of DEMs for surfaces of varying terrain types (e.g. low and high relief, vegetated and unvegetated) would assess GLAS accuracy as a function of surface conditions. To date, only very preliminary analyses using this technique have been explored. The results show reduced resolution of pointing bias parameters from that of the ocean sweep technique. However, this data provides valuable insight into the validation of instrument performance over land and ice. Optimal characteristics of DEMs to be used for GLAS calibration and validation are not completely studied and known. Pre-launch simulation studies using the GEODYN land direct altimetry will be further explored to assess required DEM characteristics, including extent, spatial resolution, horizontal and vertical accuracy and frequency content of relief and slope. The number and geographic distribution of DEM sites should also be assessed to optimize sampling frequency and to achieve a broad distribution of thermal states defined by beta and orbit angles. Based on simulation studies, a selected set of validation sites should be established where pre-launch measurements are undertaken to produce appropriate DEMs. The principal reason for focusing on land and ice direct altimetry to DEMs, in addition to the ocean sweeps, is that the DEM range comparison provides the additional capability of landform product validation.

Crossovers

The third measurement model is an altimeter crossover capability that we term "dynamic crossovers". This crossover measurement model has been implemented to take into account the small footprint of the laser altimeter along with the observed sloping terrain, and therefore, the horizontal sensitivity of these data. The dynamic crossover measurement model is discussed in detail along with its application to orbit and attitude determination for Mars Global Surveyor (MGS) in Rowlands et al. [1999]. The altimeter observations from both ascending and descending passes surrounding a crossover point trace out two curves in space. These curves contain signal from topography, orbit laser pointing, range and timing parameters. Three-dimensional polynomials are used to represent the ascending and descending curves. The crossover pair of observation, and their times, are found at the minimum distance between the curves. The crossover distance is minimized through the estimation of orbit, laser pointing and timing parameters. The observation constraint equation takes into account that the horizontal location can be changed to exploit slope. This can change the set of observations surrounding the crossover, hence the name "dynamic crossovers".

The dynamic crossover capability provides a means to calibrate timing, pointing and orbit parameters. Rowlands et al. [1999] demonstrated significant improvement in pointing, timing and orbits in support of MGS. Currently, preliminary ICESat crossover simulations have been performed that demonstrate the ability to calibrate instrument pointing biases. Prior to launch the ICESat crossover simulations will be enhanced to define sensitivities to system errors and to explore the calibration of an extended parameter set. Furthermore, the dynamic crossover technique has been applied to the analysis of SLA data. While there are far too few SLA crossover points to calibrate a full simultaneous orbit and pointing solution from crossovers alone, the technique has been used to validate the orbit, pointing and ranging solutions derived from direct altimetry. In a similar fashion, the dynamic crossover capability can also be used to validate ICESat calibration solutions and data products. Crossover points are fundamental to the determination of ice sheet elevation change, the principal objective of the ICESat investigation. Applying the dynamic crossover technique to the evaluation of GLAS crossover discrepancies provides a means to validate the ice-sheet elevation change detection at the cm-per-year level.

There is an important synergy between the direct altimetry (ocean sweeps and land DEMs) and dynamic crossover capabilities. First, both data can accurately calibrate the laser pointing corrections. However, the direct altimetry can resolve shorter temporal wavelength and local variability while the dynamic crossovers do not suffer from surface modeling errors and issues. The direct altimetry can provide a very accurate a priori estimate of pointing to properly select the crossover sections. The direct altimetry is relatively insensitive to timing biases while the dynamic crossovers are very sensitive to observation and attitude timing biases. Conversely, the direct altimetry can fully resolve range biases while the dynamic crossovers can only resolve differences in range bias due to time variation or from different satellites. The implementation of the above laser altimeter measurement models within a single system that also supports the precision orbit determination process facilitates a truly combined calibration that takes advantage of the combined strengths of each data type. Orbit, pointing, ranging and timing calibration can simultaneously be performed from a combination of calibration data including direct altimetry from ocean sweeps and detailed calibration land sites, and dynamic crossovers. These data can be accumulated over the course of the mission to strengthen parameter solutions and to observe environmental and system related temporal variations in performance.

GPS and SLR

Precision Orbit Determination (POD) is a fundamental aspect in the computation of accurate geolocation. Towards this end the POD solutions are an important ICESat product to validate. The GEODYN system will be used as an independent system to periodically produce POD solutions. The GEODYN POD solutions will be compared with the GLAS standard data POD product and the differences assessed as part of the POD validation. GEODYN is capable of producing POD solutions based on all of the available ICESat data: GPS, SLR, direct altimetry and dynamic crossovers. Each of these data types has its own strengths.

If the ICESat GPS receivers perform well, GPS will be the strongest single data type for POD. GPS data potentially allows the use of reduced dynamic techniques where large numbers of empirical accelerations can be estimated. Even so, on an observation by observation basis SLR is stronger than GPS data. Unlike GPS, SLR data provides unambiguous ranges without timing issues, so SLR data can add strength to a GPS-only solution. Often reduced dynamic techniques require the use of time correlation constraints to ensure the many empirical parameters have some coherence. SLR data can help to reduce the reliance on these constraints. SLR can also be used to validate GPS orbits. However, SLR only solutions will not have the tracking coverage of GPS and the ability to add the laser ranging as either direct altimetry or crossovers to the SLR solutions will be important to strengthen the poor SLR temporal sampling of the orbit.

Both dynamic and reduced dynamic solutions will be computed and geopotential and non-conservative force models will be tuned. With the dual frequency GPS receiver performing properly it is possible to produce highly accurate orbits from the reduced dynamic solution without significant model tuning. However, it will be important to properly tune the geopotential and non-conservative force models so that dynamic solutions based on SLR and altimetry can serve the mission in the event of a GPS failure. The differences between the dynamic and reduced dynamic solutions will serve as a performance assessment of model tuning. Orbit overlap comparisons will be used to assess orbit solution precision along with tracking data and altimeter range data residuals to assess solution performance. The POD product will ultimately be validated during the combined geolocation validation processes discussed below.

Weighting, the Key to Integration of Tracking Data Types

We intend to use only two types of information in our least squares normal equations: observations (GPS, SLR and various forms of altimetry) and time correlation constraints for empirical acceleration parameters. Each of these forms of information has a weight which scales it as it is summed into the normal equations. These weights can have a large influence on how well various tracking data types are fit by the solution and on the parameters which are estimated by the solution. We intend to create solutions obtained with various weighting schemes and judge them with a series of tests. In the beginning stages, candidate solutions will be "weeded" by using overlap tests and subset solution tests and also by looking at how well each solution fits the tracking data (residual analysis). In the final stages of the process, DEM matching will be used to discriminate between solutions.

Overlap tests and subset solution tests as applied to weighting orbit solutions are described by Rowlands et al. [1997]. Very similar tests can be applied to geolocated altimetry. Geolocation overlap and subset solution tests gauge the quality of all geolocation parameters. Even so, they can and will be used to judge subsets of parameters, like pointing biases. At the beginning stages of the weight determination process we will perform solutions for geolocation parameters from altimetry holding orbit parameters fixed to values determined from GPS and SLR data. Geolocation overlap and geolocation subset tests together with residual analysis will be used to gauge the quality of the various solutions for non orbit parameters obtained by changing the weighting of the altimetry data types.

The overall procedure will start with the determination of weights for orbit only solutions from GPS data and SLR data using orbit overlap tests, subset solution tests and residual analysis. The best orbit from this process will be held fixed and used in the determination of all of the parameters (except orbit parameters) which can be estimated from the various forms of altimetry. Range residuals and geolocation tests will be used to help judge the relative weighting of the various altimetry data types. Finally, we will move on to simultaneous solutions for orbit, pointing, instrument and geophysical parameters. Here, what needs to be determined is a single scale factor to be applied to all the weights of the individual altimetry data types that have been determined previously. This scale factor will be used to multiply all the altimetry weights in the combined solution. The weights determined for the GPS and SLR observations in the orbit only tests will not be altered. Geolocation tests, orbit tests and residual analysis will be used to determine the altimetry scale factor.

Some additional points need to be made about the weights that go into an orbit only solution from GPS and SLR. There are three weights: the GPS observation weights, the SLR observation weights and the weights assigned to the time correlation constraint equations for empirical accelerations. The GPS tracking data type will be the fundamental data type. We will assign each GPS observation a weight of 10000 which corresponds to a standard deviation of 0.01meter. The other weights will be determined relative to this. As far as the weighting of time correlation constraints, there are two factors which need to be determined: the correlation time and the background weight (the weight at the correlation time). Experience has shown us that a correlation time corresponding to one quarter revolution (about 1450 seconds for ICESat) generally works well. A first determination of the background weight will be made from looking at GPS only solutions. When SLR data is first added, this weight will be used. In other words, the weight for SLR will be determined holding the GPS weight and the time correlation weights fixed. After the SLR data weight has been determined, it will be investigated if the time correlation weight can be decreased. It should be true that as more data is added, time correlation will be less necessary. A similar situation will exist when altimetry is added in. After the altimetry scale factor described above is determined, it will be investigated if the time correlation can be down weighted.

6.7.6. Precision Attitude Determination

The Precision Attitude Determination (PAD) is also a fundamental aspect in the computation of accurate geolocation. The direct validation of the PAD is difficult due to limited independent data, however several things can be done towards the validation of this data product. First, the primary PAD data (star tracker and gyro data from the GLAS Stellar Reference System (SRS)) can be evaluated with an independent software system. The GSFC Flight Dynamics Facility Attitude Determination System (FDF ADS) can be used to process the raw SRS data. The independently computed PAD and FDF ADS solutions can be directly compared to explore any significant systematic errors. Within the FDF ADS software several different solution techniques can be applied (e.g. frame-by-frame geometric, Kalman filter, batch least squares). The solutions based on the differing techniques can also be compared to explore systematic errors. The SRS data residuals and attitude solution overlaps will be used as an indicator of solution performance and precision. Independent spacecraft star tracker and gyro data used to support flight operations can be reduced in combination with the instrument SRS data. Combination solutions with optimal weighting will be explored for attitude product performance improvement. Furthermore, the combination solutions can serve to calibrate the spacecraft sensor data. This calibrated spacecraft sensor data can then be used to serve the mission in the event of an instrument SRS failure. The PAD and FDF ADS attitude solutions will ultimately be validated during the combined geolocation validation process discussed previously.

6.7.7. Profile and Waveform Matching to Digital Elevation Models

Introduction

A strength of the Geodyn combined solution described above is the highly accurate determination of instrument calibration parameters, and temporal trends in those parameters, based on processing direct altimetry and cross-over data simultaneously with spacecraft tracking data. The associated analysis of residuals and segment subsets and overlaps for geolocated laser footprint ground tracks can assess the relative accuracy and reproducibility of the resulting geolocation. However, residual analysis and segment tests do not assess the absolute accuracy nor systematic errors of a geolocation result. Furthermore, consistency in geolocation results achieved by the ICESat project solution and the Geodyn combined solution would serve to validate the ICESat project solution. However, if the geolocation solutions differ, then a method that quantifies each of their absolute accuracies will be necessary in order to assess the solutions.

Profile Matching

The comparison of geolocation results to accurate DEMs provides a means to assess the absolute accuracy and systematic errors of the laser footprint position, and to evaluate alternative geolocation results. The comparison can be done based on differencing elevation profiles or waveforms with respect to the DEM. In the former, the elevation for each footprint along a profile is differenced with respect to the corresponding DEM elevation. The standard deviation of the differences establishes a residual for the profile as a whole. By computing the profile residual for positions systematically shifted with respect to the DEM in X, Y, and Z, the position of the residual minima establishes the proper geolocation of the profile. This approach has been developed to assess the geolocation accuracy of SLA profiles (Garvin et al., 1998).

Profile matching requires that a geolocation solution is available to initiate the search for the residual minima, as would be provided by the ICESat project or Geodyn combined solutions. The approach also requires that the DEM accurately represents surface elevations, that it is of sufficient spatial extent and resolution, and that it represents a sufficiently complex surface so that there is sensitivity to tested changes in profile location. There are trade-offs between each of these DEM attributes. For example, a DEM covering a small area with very high resolution and accuracy may in fact provide a less sensitive test than a DEM covering a much larger area with less resolution and accuracy. The latter would include many more laser footprints and a greater diversity of terrain relief, increasing the statistical power of the technique. Pre-launch simulations are required to establish DEM characteristics most suitable for ICESat profile differencing. In particular, the potential use of DEMs covering regional to continental scales (e.g. USGS 30 m DEMs, NIMA 90 m DTED, SRTM 30 m DEM) should be compared to local DEMs, of much higher accuracy and resolution, to be acquired by airborne laser altimeter mapping systems along ICESat ground tracks.

Waveform Matching

The waveform matching approach potentially has greater sensitivity in assessing footprint geolocation than the profile matching approach, because there are many more observables; the waveform amplitude in many height increments as compared to a single elevation. Rather than differencing a footprint elevation to a DEM elevation, waveform matching is accomplished by minimizing the residual between within-footprint surface height distributions as recorded by the observed waveform and a simulated waveform derived from the DEM. The residual can be computed for an individual footprint or a group of footprints. The DEM must be of very high accuracy and spatial resolution, significantly better than the ICESat 70 m footprint size, so that there are a sufficient number of within-footprint elevation values from which to simulate a waveform. Again, by shifting the position of the laser footprints with respect to the DEM in X, Y, and Z in order to minimize the observed-to-simulated waveform residual, the geolocation of the laser waveforms can be assessed. The DEM measure of within-footprint slope and roughness can then be used to validate these geophysical parameters inferred from the observed waveform. In addition to validating footprint geolocation, slope, and roughness, attributes of the laser beam quality such as the beam diameter, circularity, and pulse width can also be assessed. This is accomplished by incrementally varying these parameters in turn and searching for a waveform residual minima. It is likely that iteration between position and beam quality searches will be necessary to identify the residual minima in the multi-parameter search space.

To use the waveform matching approach, the spatial variation of reflectance at the laser wavelength (1064 nm) within the footprint must be minimal or independently known, because the simulated return intensity depends on the reflectance of the surface elements. In addition, the surface elevation must be sufficiently complex at the footprint-scale, rather than profile-scale, to yield sensitivity during matching. And the method of simulating waveforms from the DEM must be validated in order to ensure that residual minima are not corrupted by simulator errors.

Example of Waveform Matching

The waveform matching approach was first described by Blair and Hofton [1999], in which they compare laser altimeter waveforms for 25 m diameter footprints acquired by the airborne Laser Vegetation Imaging Sensor (LVIS) to simulated waveforms. The LVIS footprints were contiguous along- and cross-track, providing a fully illuminated ’image’ of waveforms. The simulated waveforms were derived from a DEM constructed from very-high resolution elevation data acquired by a helicopter-borne scanning laser altimeter (FLI-MAP). The altimeter data consisted of first-return ranges to 10 cm diameter footprints spaced approximately every 30 cm across a 2 x 4 km area of dense, tropical rain forest in Costa Rica. These data were gridded, creating a DEM of 33 cm horizontal spacing and approximately 10 cm vertical accuracy. As a function of height, the waveform simulation first summed each DEM grid elevation within a circular footprint after convolution with functions that represented the LVIS along-beam (i.e., pulse width) and across-beam (i.e., footprint diameter) Gaussian energy distributions. The sum was then convolved with the impulse response of the LVIS receiver, yielding the simulated waveform. The simulation did not determine absolute magnitude of the waveforms (i.e., number of photoelectrons received), no optical or electronic noise functions were added, and the reflectance across the footprint was held constant, assuming the dense canopy reflectance was everywhere uniform.

A total of 1150 LVIS and simulated waveforms were compared from a 0.5 x 2 km area. The similarity between each observed and simulated waveform pair was assessed using the Pearson correlation. Maximizing the mean correlation for all waveforms (equivalent to a residual minima) was used to search for the spatial correspondence between the LVIS waveforms and DEM, as well as for beam quality parameters. Shifts of the observed waveforms with respect to the DEM in west, north and vertical directions all yielded well defined correlation maxima, as did variation of pulse width and footprint diameter. Departure from footprint circularity was not tested for. The precision in determining the maximum correlation was 0.01 m for the vertical shift and pulse width variation, and 0.1 m for the east, west, and diameter parameters.

The high precision in determining spatial correlation and beam quality achieved by Blair and Hofton [1999] was due to the great diversity of vertical structure present in the rain forest canopy, the relatively small LVIS footprints and their spatial density, and the extremely high resolution of the FLI-MAP scanning laser altimeter data. Unvegetated surfaces, presenting much less vertical structure at short length-scales, will be less sensitive to geolocation shifts or variation in beam quality parameters. Furthermore, the ICESat footprint encompasses nearly eight times the area of the LVIS footprints used by Blair and Hofton [1999]. Larger footprints will typically include a more complete distribution of surface elevations, yielding smoother waveforms less suitable for unique matching of distinctive waveform features. In addition, ICESat's profiles of non-contiguous footprints will require a much larger DEM extent as compared to the dense LVIS waveform image in order to include the same number of waveforms in a residual analysis. And collection of data at the FLI-MAP resolution requires a helicopter-borne laser altimeter system that is impractical for generating DEMs of numerous, large or remote sites.

Cal/Val Activities

The waveform matching approach using simulated ICESat waveforms must be assessed prior to launch in order to establish the DEM characteristics (resolution, accuracy, extent, length-scales of vertical structure, knowledge of the spatial variation in reflectance) required for validation purposes. The validity of the waveform simulation method must also be assessed prior to its use in matching observed ICESat waveforms.

To those ends, the following pre-launch activities will be conducted. First, the GLAS waveform simulator (Abshire et al., 1994) and its DEM capability, which is currently being incorporated into the simulator, will be tested in order to assess its validity. The GLAS simulator includes a complete instrument receiver model specific to the GLAS parameters and noise characteristics and therefore, unlike the more generic Blair and Hofton [1999] simulation, includes predictions of signal and noise levels. The DEM capability will also include variation of reflectance for each grid element, allowing simulation of non-uniform targets such as mixtures of vegetation and bare earth, or ice and exposed rock. The GLAS simulator will be tested, and tuned as needed, by comparing waveforms simulated from high-resolution DEMs to airborne large-footprint waveforms acquired by the Bigfoot system [Bufton, 1993]. Spatially coincident Bigfoot and high-resolution DEM data sets include areas in Greenland and western Washington State. The coincident LVIS and FLI-MAP data sets described above, or others like it, will also be used if available.

Second, sensitivity studies of various kinds of in-hand DEMs will be conducted to identify appropriate characteristics for profile and waveform matching. The studies would consider DEM resolution, accuracy, extent, vegetated versus non-vegetated, rugged versus smooth topography, and uniform versus spatially varying reflectance. The studies will establish to what degree DEM matching can contribute to ICESat product validation given the characteristics of the DEMs available to, or collected by, the ICESat project. DEMs to be evaluated include: (1) Greenland ice sheet DEMs acquired by NASA's Airborne Terrain Mapper (ATM), (2) western United States DEMs to be acquired by ATM in the summer of 2001 at selected ICESat orbit track cross-overs, (3) a 1.8 m resolution DEM of a 2350 sq km area of western Washington State acquired for the Puget Lowland Lidar Consortium, of which NASA is a member, utilizing a commercialized version of the ATM system, and (4) a DEM of the Bagley Ice Field and Seward Glacier in Alaska derived from airborne IFSAR mapping (3000 sq km with 10 m resolution and 3 m vertical accuracy) and high-resolution laser profiles (1.2 m resolution and ~ 0.3 m vertical accuracy). Through these sensitivity studies, existing software tools for conducting profile and waveform matching tests will be refined and readied for post-launch use. The observed and simulated waveforms from these diverse settings will also be input to the ISIPPS waveform processor in order to validate the derived geophysical parameters (elevation, slope, roughness) by comparing to the same quantities calculated from the high-resolution DEMs. During post-launch calibration and validation, ICESat profile and waveform matching will be conducted where cloud-free data is collected across those DEMs having appropriate characteristics for the matching techniques, as identified by the simulation studies.

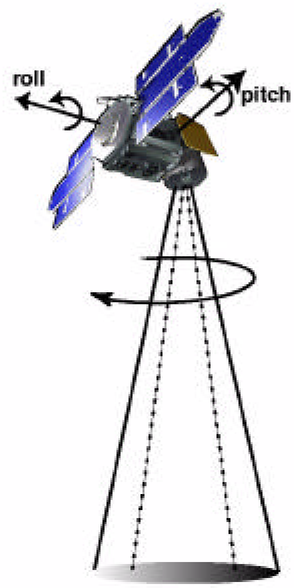


Fig. 6.7.2 Ocean sweep maneuver for the determination of pointing biases. The maneuver requires attitude commands in the roll and pitch axes to produce a conical motion about the nadir direction. An off-nadir angle of at least 5° is planned and a complete cycle to complete the cone will be used on long passes over the Pacific. Figure created by Scott Luthcke.

6.8 Aircraft Surveys

A major part of the GLAS validation program will involve comparison of GLAS-derived estimates of surface elevation with those derived from precise aircraft laser-altimetry surveys, as described above. Aircraft flights are planned, both before and after ICESAT launch, to survey selected regions of both ice and land topography using NASA's Airborne Topographic Mapper (ATM) instruments. Flights will be by the NASA P-3 aircraft based at Wallops or, where appropriate, Twin Otter aircraft operated by NOAA and NSF. We have attempted to coordinate planned surveys with other ATM activities that might be supported by either NASA's R&A Program or by other Agencies. However, support for any such work has yet to be approved.

6.8.1 Assumptions

(i) ICESAT launch is planned for December, 2001, with possible delay by not more than 3 months.
(ii) GLAS will begin delivering data to the Team approximately one month after launch, with the possibility that very early data will be flawed for some unanticipated reason.
(iii) Funding support will be available to support aircraft acquisition and processing of cal/val data plus some data to complement GLAS data.
(iv) Aircraft surveys will be done with the NASA/Wallops ATM aboard the NASA long range P-3 aircraft, except where otherwise indicated.
(v) Members of the GLAS Team will use these data for cal/val activities etc, under their Team funding.
(vi) Validation flights over ice will be made as closely in time as possible to ICESAT overflight, whereas those over land can be made before or after overflight.
(vii) The "flying season" in Greenland is late April to August, for flights out of Thule, and slightly longer for Sondestrom. The season for Antarctica is early November through late January.

These assumptions suggest that over-ice validation should be delayed until after April, 2002, but that over-land surveys can be flown before then.

6.8.2 Planned aircraft surveys

May, 2001:
Greenland flights are scheduled in May by NASA's R&A program, and we plan GLAS-related surveys during this period of selected ice flow lines with both the ATM and NASA's ice-sounding radar (both instruments are flown routinely to support R&A activities). Acquired data will be used to map synchronous layers within the ice sheet, using a technique already developed by M. Fahnestock and W. Abdalati, which will help test and improve ice-sheet models that will be used for interpretation of GLAS measurements of ice thickening/thinning rates, including one under development for ICESat by Weili Wang. Also, if the University of Kansas shallow-layer radar is part of the R&A payload, data will be acquired to improve assessment of the spatial and temporal variability of snow-accumulation rates, information that is crucial to the separation of short-term elevation changes from long-term ice-thickness changes.

June, 2001:
Surveys of 4 or 5 validation sites in arid parts of south-western USA. These sites will be approximately 100 km X 100 km, with flights primarily along mapping-phase orbit tracks, which are approximately 15 km apart at these latitudes. Consequently, each vaidation site will include about 6 ascending and 6 descending orbits. At some locations, 8-day repeat orbits will also be included. We expect to cover all orbit tracks within a single site in one flight, with a single pass along each track. Roll errors will be minimized using data obtained at the many flight-track crossing points. A candidate site is shown in Fig. 6.8.1.

Fall, 2001:
Possible flights over desert regions in Saudi Arabia in conjunction with survey flights sponsored by USGS. These flights would probably be aboard the P-3, but could be aboard a Twin Otter. They would be over arid terrain, ranging from smoothly undulating to rougher, steeper surfaces, and probably all flights will be along mapping-phase orbits. Detailed planning awaits confirmation that the survey will take place, and will be done in consulatation with USGS personnel with expert knowledge of the local terrain.

Late 2001/early 2002:
Surveys of an arid region in Antarctica known as the Dry Valleys, where there is little snow cover, in collaboration with NSF and USGS. Flights will be by a Twin Otter chartered by NSF from a Canadian company that has already worked successfully with Bill Krabill's group and the ATM to survey Canadian ice caps. Flights will be primarily along mapping-phase orbits, and will be planned in conjunction with flights required by USGS to map large parts of the Dry Valleys.

April/May, 2002:
Surveys along ascending and descending orbit tracks over the Greenland ice sheet, and two long orbit tracks over sea ice. These will allow us to assess GLAS performance over ice soon after launch, and to provide data users with a quantitative estimate of GLAS errors when operating over ice. Our simulations, using detailed aircraft laser-altimeter measurements of Greenland surface topography, indicate that the ice surface is sufficiently undulating to permit analysis of the Greenland cal/val data to estimate values of GLAS range and pointing bias to accuracies of a few cm and less than one arc second respectively.
These surveys will be flown out of Thule Air Force Base, N Greenland, as soon as weather conditions permit - April/May, 2002. If the R&A program also supports a Greenland flight program in FY-2002, we shall coordinate logistics and flights to minimize costs to both programs. The prime objective of the ICESAT flights will be GLAS validation, but availability, through the R&A program, of both ice-sounding and shallow-depth radar would significantly enhance the value to GLAS of the surveys.
Final selection of the orbit tracks to be surveyed will depend on whether ICESAT is still in its Verification Phase and on weather conditions at the time. Meanwhile, we have selected several candidate orbit tracks from both the verification phase and mapping phase to assess flight

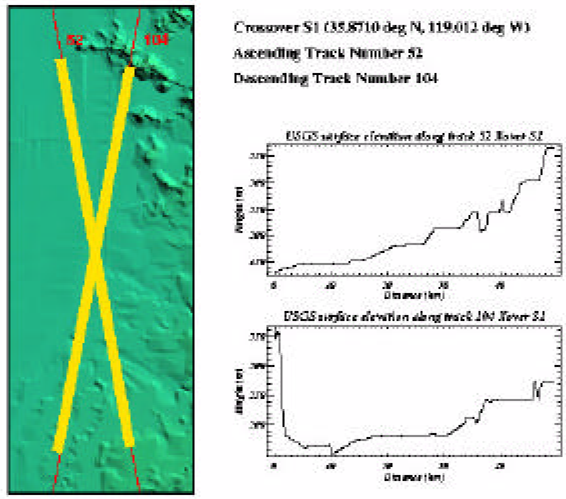


Fig. 6.8.1 Western U.S. Calibration/Validation Site in Mojave Desert

duration etc, and to give an indication of their proximity to Thule. Survey flights will be phased so that they are timed within a day or two of ICESAT overpass.

Beyond 2002:

GLAS aircraft activities during 2003 and later will depend heavily on these factors:

(i) Actual GLAS performance as revealed by the above surveys and other components of the GLAS validation plan. An apparent drift in range or attitude bias, for instance, may indicate the need to resurvey validation sites in the western US.

(ii) Missions of opportunity, such as those listed above for Saudi Arabia and Antarctica. In order to take advantage of such opportunities, we recommend sufficient flexibility in both survey logistics and financial support to allow incorporation of missions of opportunity at comparatively short notice.

(iii) Patterns of ice-elevation change revealed by GLAS. These may indicate the need for aircraft surveys of, for instance, narrow, sinuous outlet glaciers apparently undergoing major changes, but with only sparse coverage by ICESAT. Or they may indicate a need for ancillary information, such as ice thickness, to improve interpretation of the GLAS measurements.

6.8.3 Task allocations

6.8.3.1 Aircraft surveys

All surveys using the ATM will be coordinated and planned in detail by W Krabill (Wallops Flight Facility). He and his group have broad experience of successfully conducting such surveys over ice and over land using both the P-3 and Twin Otter aircraft. He will also be responsible for processing and quality assessment of the data to produce 3-D coordinates of all ATM footprints and, where required, higher level products. All this work will be done in close consultation with GLAS Team members directly involved in associated cal/val activities. Each of these Team members will be responsible for independent error assessment of the ATM products associated with their aspects of the overall effort.

6.8.3.2 Over-ice cal/val

R. Thomas has the prime responsibility for the analysis of over-ice data for overall GLAS performance over ice sheets, and estimation of GLAS range and pointing bias. This will be done in consultation with J. Zwally and C. Bentley. R. thomas also will take the lead on validation of sea-ice products derived from GLAS data, with C. Bentley taking the lead on validation of "roughness" products derived over the ice sheets. The group working with R. Thomas under GLAS support includes B. Csatho and S. Filin at Ohio Sate University, and C. Martin, S. Manizade, and J. Sonntag from EG&G.

6.8.3.3 Over-land cal/val

B. Csatho, working P. Chavez (USGS) and R. Thomas and W. Krabill, has taken the lead on site selection in the western US and the Antarctic Dry Valleys, and W. Krabill's ATM group will select Saudi Arabia sites working with USGS colleagues.

B. Minster has prime responsibility for the analysis of data from the western US, with the R. Thomas group applying an independent analysis to some of the data from all land sites. In addition, J. Bufton's group will use all land data in the "integrated residual analysis" described in Section 6.7. D. Harding, working with J. Bufton, will take the lead on validating GLAS data over forested regions near Seattle, using aircraft data collected under separate NASA funding.

6.8.4. Summary

Table 1 summarizes aircraft surveys with the NASA/WFF Airborne Topographic Mapper (ATM) over the next two fiscal years that could contribute to GLAS validation, and Table 2 lists other ATM activities that have been proposed, to show opportunities for flight coordination and to assess the potential work load for the ATM group.

Table 6.8.4.1. Planned GLAS Cal/Val aircraft surveys

Date	Location	Purpose	GLAS PI
2001			
May	Greenland	Map elevation + internal layers for model improvement	Krabill/Zwally
June	West US	Survey validation sites	Csatho/Krabill
Fall	Saudi Arabia	Survey desert validation region	Krabill/Thomas
2002			
January	Antarctica	Antarctic Dry Valleys	Csatho/Krabill
April/May	Greenland	Mapping surveys	Thomas/Krabill

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The above references are available at http://www.csr.utexas.edu/glas/, except for references published in archival journals.